Spring-Based Helmet System Support Prototype to Address Aircrew Neck Strain

By:
Steven Fischer, PhD, R.Kin
Joan Stevenson, PhD
Susan Reid, MSc. Mech. Eng
School of Kinesiology and Health Studies
Queen's University

Markus Hetzler, P.Eng
Thumbprint Solutions Inc.

Prepared By:
Canadian Institute for Military & Veteran Health Research
Queen's University
111 Botterell Hall, Kingston, ON K7L 3N6
Contractor's Document Number: Task 31
Contract Project Manager: Michael Schaub, MPA, 613-533-6000 ext 79363
PWGSC Contract Number: W7714-125624/001/SV
CSA: Philip S.E. Farrell, PhD, Defence Scientist, 416-635-2000 ext 2305

Contract Report
DRDC RDDC 2014-C187
June 2014

Principal Author

Original signed by Steven Fischer

Steven Fischer

Assistant Professor, Queen's University

Approved by

Original signed by [Approved By Name]

[Approved By Name]

[Approved By Position/Title]

Approved for release by

Original signed by [Released By Name]

[Released By Name]

[Released By Position/Title]

In conducting the research described in this report, the investigators adhered to the policies and procedures set out in the Tri-Council Policy Statement: Ethical conduct for research involving humans, National Council on Ethics in Human Research, Ottawa, 1998 as issued jointly by the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council of Canada and the Social Sciences and Humanities Research Council of Canada.

Abstract

The Royal Canadian Air Force Griffon helicopter aircrew are known to have extremely high incidence of chronic, debilitating neck pain. Fischer et al. (2013) identified that unbalanced moments due to head-borne equipment (i.e., helmet with NVG) were a particular concern since the current solution was to add more weight (battery pack and counterweight (CW)) as a counterbalancing force. Three concepts were proposed to improve the helmet-NVG system with one commissioned by DRDC as a short-term solution to mitigate neck strain/pain. A biomechanical model was developed which revealed that a constant force of approximately 8N was better than the current system. Two prototype designs were engineered and developed using rapid prototyping technology; one design altered the moment arm of a linear spring system while the other altered its force. One prototype design was evaluated using a test battery to simulate pilots' and flight engineers' duties. The new counter-measure prototype was either equal to or better than the helmet-NVG and Helmet-NVG-CW conditions on 7/8 variables tested. Both concepts were demonstrated to 400 Sqn flight crews and received overwhelming positive responses with some suggestions for improvements. Based on these studies, the new counter-measure device should be refined to be production-ready and evaluated through normal military channels.

This page intentionally left blank.

Executive summary

Spring-Based Helmet System Support Prototype to Address Aircrew Neck Strain:

Steven Fischer; Joan Stevenson; Susan Reid; Markus Hetzler; DRDC Toronto CR [enter number only: 9999-999]; Defence R&D Canada – Toronto; June 2014.

Introduction: Many researchers have investigated the high incidence rates of neck pain in RCAF Griffon helicopter flight crew to determine root causes. Fischer et al. (2013) identified that unbalanced moments due to head-borne equipment (i.e., helmet with NVG) were a major concern, especially since the current solution was to add more weight (battery pack and counterweight (CW)) as a counterbalancing force. Since neck pain and injuries persist and no NVG design changes are scheduled in the near future, DRDC commissioned our cross-functional development team, consisting of academia (Queen's University) and industry (Thumbprint Solutions Inc.), to identify possible near-term solutions. In our Phase 1 report, three design concepts were proposed to reduce the neck moments and forces of the current helmet-NVG system. One design concept was commissioned as a near-term cost-effective counter-measure solution. Hence, the aims of Phase 2 were to: develop a simple biomechanical model that would assist the team in making design decisions, develop counter-measure devices using rapid prototyping technology; conduct lab-based and field-based human trials to verify effectiveness, identify changes needed in prototype design, and provide DRDC with a prototype counter-measure device as well as a written report.

Methods: A 3D static biomechanical model was developed to calculate the forces and moments about the occipital condyles of the head only. This model was used to: determine the magnitude of moments and forces resulting from the current helmet system; estimate the moment needed (approximately 1.2 N.m or 8N at 0.15m) to create a counter-balancing force thereby eliminating the CW (and possibly battery pack) from the helmet; and, apply these findings to the design of a new counter-measure device. Then, prototype designs were engineered and constructed at Queen's and Thumbprint Solutions using commercial parts and rapid prototyping technology. Two prototype designs were manufactured: one design altered the moment arm of a constant spring system while the other altered its force to provide adjustability. Both countermeasures devices were worn and evaluated at CFB Borden by 400 Sqn ALSE Personnel, flight engineers and pilots. However, only one prototype device was evaluated in lab tests using simulated flight crew duties during a night mission under three conditions: helmet-NVG, Helmet-NVG-CW and the new counter-measure device. Outcome variables included: time taken, perceived rate of exertion, and neck muscle electromyography. The results were discussed under functional, operational, and ergonomics requirements as well as known manufacturing and economic constraints.

Results: Two physical prototypes were produced which were very similar in that they utilized robust, well-known purely mechanical technology. Both prototypes used a constant force spring-based cable that connected the helmet to the body-worn flight vest. The first prototype had fixed end points and an adjustable lever to change the moment arm length. The second prototype had the same cable system, except that adjustability was created by changing the force level and it included a track on the helmet. Lab testing revealed that the counter-measure device clearly

reduced muscular demand to at least, or better than daytime values. It reduced head-borne mass by 10%, improved time to complete vigilance tasks, improved endurance with respect to both the head+NVG system and head+NVG+CW system and was subjectively ranked as the best condition. In other words, it either matched or exceeded the other two conditions in 7/8 tests. In terms of feedback from Griffon flight crews, they provided an overwhelmingly positive response, with one pilot asking to wear it that same night on his scheduled night-flight. They also provided excellent feedback on preferences and movements where the counter-measure designs were not optimal. Both the flight-crews and maintenance personnel felt that the prototypes were very close to trial status and posed no operational risks. While it is still early in the development process, early manufacturing reviews suggest that the system can be manufactured in low, medium or high quantities using common engineering materials.

Significance: With the current rates of chronic, debilitating neck pain among Griffon helicopter flight crews, it is important to provide short-term solutions if changes in the NVG are not forthcoming soon. Indeed, any military unit (army, navy, air force) that uses NVG can benefit from this counter-measures design concept. The new counter-measure device, reduces the head-borne mass by 10% and, based on the biomechanical model, reduces neck moments (torques) by 20%, which is comparable to the head-helmet system alone. For these reasons, both flight crews and student participants noticed immediate improvements and consistently ranked it first. Based on these studies, the new counter-measure device should be refined to be production-ready and evaluated through normal military channels.

None of the components present a technical challenge and the expected production costs are very reasonable.

Future plans: This work has shown that the new counter-measure device can be developed to improve the current Helmet-NVG system. However, some additional development is needed to improve certain performance limitations. Once completed, then flight-ready prototypes or early-stage production-ready versions need to be manufactured so that the new counter-measure device can be evaluated within the aviation testing environment and flight crew evaluation framework. The way ahead requires the support of military/government sources either by way of: funding its development or leverage funding to seek funding elsewhere or documented support so that private sector funds can be solicited for investment. These final two approaches require a solid business plan and a commitment to invest in this short term solution once developed and evaluated. In summary, the new counter-measure device is an excellent near-term solution. How to proceed with its advancement is yet to be decided.

Table of contents

List of figures

List of tables

Acknowledgements

The authors would like to thank Major Lyle Holbrook and his fellow members of the 400 Squadron, located at CFB Borden for their insightful thoughts and constructive feedback on the current design iteration.

This page intentionally left blank.

1 Background, Aim and Description of the Design Process

1.1 Background

Aircrew neck pain poses a considerable challenge to the Canadian Forces (CF). Preliminary data from a current study conducted by Defense Research and Development Canada indicates that 56% of active CF Griffon aircrew report neck pain; where 78 aircrew members have been grounded or have grounded themselves as a result of neck pain. While specific injury mechanisms are still being understood, the mass on the head and particularly the added mass and location of the night vision goggles (NVGs) are the most likely contributors to the neck pain problem (Harrison et al., 2014).

NVG-induced neck strain is a concern amongst the helicopter aircrew of many national militaries, including the United Kingdom (Wickes et al., 2005), Sweden (Ang et al., 2005; Thuresson, 2005; Ang and Harsm-Ringdahl, 2006; Ang, 2007), the Netherlands (van den Oord, 2010a, van den Oord et al., 2010b), the United States (Butler, 1992; Fraser et al., 2006; Walters et al., 2012), and Canada (Adam, 2004; Forde, 2009; Harrison, 2009; Salmon, 2009). The rates of injury vary from nation to nation but the Canadian data show a lifetime prevalence of neck pain in the range of 81-84% for CF helicopter pilots and flight engineers who operate the CH-146 Griffon helicopter and this prevalence exceeds 90% amongst a subset of the population that have logged more than 150hrs of NVG-flight hours during their career (Adam, 2004).

The possible causes that contribute to the occurrence of neck pain among CF helicopter aircrew are multifactorial. Helmet mass, distribution of the helmet system masses, number of flight hours logged with NVG, use of NVG+CW, height of crew members, vibration of the helicopter, in-flight posture required to perform essential duties, overall fitness and neck/shoulder specific fitness of the crew member are just some of the factors identified in the literature as being contributory. Although root causes of pain and dysfunction are multifactorial and affect both pilots and flight engineers, the research highlighted below is focused specifically on physical loading factors for helicopter pilots only. Based on the scientific literature, the following findings clearly point to the NVG as being a large contributor to the neck pain.

- Posture, low +Gz forces, and vibration while using NVG, overall weight and weight distribution are reported as perceived causes of neck pain amongst aircrew (Wickes et al., 2005; van den Oord et al., 2010; van den Oord et al., 2012).

- There was increased time spent in a flexion or head-down posture during simulated NVG missions as compared to day missions which increased the neck muscle requirements (Forde et al., 2011).

- There was increased muscle perfusion of oxygen in the trapezius muscles during simulated NVG missions as compared to day missions: this occurred regardless of cockpit seat side (Harrison et al., 2007a, b, c).

- Wearing a helmet alone can cause an 18% and 28% increase in muscular activity above rest in the sternocleidomastoid and cervical erector spinae muscles respectively but wearing a helmet with NVG causes an additional 29% and 34% increase from the helmet only condition (Sovelius et al., 2008).

- Wearing NVG reduces the field of view to 20-30% of daytime viewing, thus increasing the postural requirements for the same tasks (Craig et al., 1997; Geiselman and Craig, 1999).

- Wearing NVG shifts the centre of gravity forward and up, thus increasing the distance of the perpendicular moment arm while also requiring an increased muscular force to compensate for its weight (Sovelius et al., 2008).

- Wearing either NVG or NVG plus counterweight caused changes in posture that resulted in increased moments, peak loads, cumulative loads, and shear forces as compared to simulated day missions (Forde et al., 2011).

- Although vibration is an issue for helicopter pilots because it is roughly doubles in the head/neck accelerations when compared to the back, only theoretical evidence has demonstrated that NVG's exacerbate the problem (Chen et al., 2007; Chen et al., 2009).

- The weight of the NVG helmet alone, prior to loading as a result of vibration or exposure to G-forces, is significant enough to increase the muscular activity of the neck musculature (Sovelius et al., 2008).

- Sovelius et al. (2008) suggested that lowering the location of the center of gravity of a helmet's weight has a more significant impact on relieving cervical muscle loading than decreasing the weight of the currently used NVG systems.

- The worst centre of gravity location of the helmet plus NVG is forward and upward of the head's centre of gravity. Unfortunately, this is the situation for the HGU-56P helmet and NVG (Forde et al., 2011).

- Use of the counterweight combined with the NVG on the helmet lowers the centre of gravity but not sufficiently. In addition, the impact of the counterweight only helps reduce neck moments in upright postures but has no effect in flexed non-neutral postures (Thuresson et al., 2005b; Harms-Ringdahl et al., 1996).

- In a laboratory setting with 4kg and 6kg helmets, aircrews preferred to wear a heavier but balanced helmet for a prolonged period of time as compared to a lighter helmet with centers of gravity similar to the current CF model (Gallagher et al., 2007).

The obvious and immediate solution to the above concerns is to find ways to reduce the mass and mass distribution of the helmet system in addition to other personal and work-related approaches. However, this requires an extensive redesign of the existing helmet and NVG systems, which is both time and cost intensive. Therefore, a short term solution is required to alleviate some of these concerns through the development of a helmet system support device. This report describes the design, development and verification of a device to meet this need.

1.2 Aim

The aim of this project was to develop, verify and refine an engineering-based solution to address aircrew neck strain. In accordance with the finalized statement of work, this aim was achieved by completing the following activities:

1. determine the biomechanical benefits of a spring-based helmet system support;
2. produce a working prototype of a spring-based helmet system support, as described in Fischer et al (2013);
3. generate a plan to verify the design concept using human participant trials;
4. perform a verification evaluation of the prototype, where results can be used to inform refinement;
5. write a summary report that details the biomechanical benefits, design process, design specifications, and verification and refinement; and
6. demonstrate a prototype device at the final contract meeting.

1.3 Description of the Design Process

A standard engineering/ergonomic design process was employed. As illustrated in Figure 1, the team worked through a series of concept development stages. In accordance with CSA standard Z1004-12 (Workplace Ergonomics – A management and implementation standard), ergonomic principles were considered at each stage in the design process. A brief description of the methods employed within each stage follows.

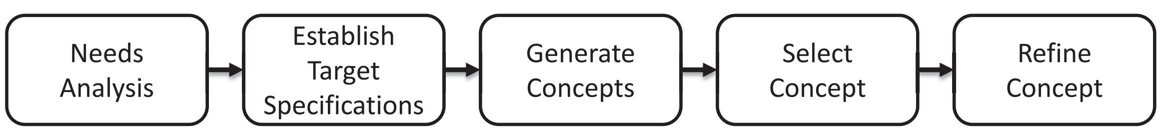

Figure 1 – An illustration of the overarching design process employed to develop the prototype

1.3.1 Needs Analysis

The intent of this stage was to determine the specific needs of aircrew to be addressed. Needs were identified through three sources: as previously described by Fischer et al., (2013), based on informal discussion with members of the aircrew community, and in consultation with members of the DRDC neck strain project team. The compelling need was a near-term solution to help mitigate or at least reduce aircrew neck pain in the short term. This near-term solution is intended as a stopgap measure until the root cause (heavy helmet and NVG system) can be addressed.

1.3.2 Establish Target Specifications

The intent of this stage was to establish specifications to inform the design. Functional, operational, and ergonomics requirements were established, in considerations of known manufacturing and economic constraints (i.e. it must be cost effective so it must be simple and easy to build with minimal parts). While a more comprehensive list of design specifications in included in Annex A, the following list of 10 overarching specifications were identified and used to inform the concept design:

1. Reduce the mass on the head
2. Lower the inertia of the head-helmet system
3. Reduce neck muscular demand (to day flight levels at a minimum)
4. Reduce overall neck compression and moments
5. Accommodate a full range of motion
6. Allow for individual user adjustability (adjustable off-load)
7. Be easy to engage and disengage
8. Low intrusion on operational environment
9. Robust
10. Cost effective to manufacture

1.3.3 Generate Concepts

The intent of this stage was to develop preliminary design concepts and variants that would be likely to meet the design specifications. During this stage, supported by the biomechanical proof-of principle described in Section 2, the research team quickly converged on the notion that a constant force spring-based approach was well suited to achieve the desired requirements. Building from that concept a divergent thinking approach was applied, where two separate design teams were tasked with designing variations of the spring-based concept, giving consideration to both adjustability and attachment points (upper and lower ends). A divergent process was employed for two reasons. First, this process allowed each team to generate its own ideas without being constrained by the ideas of the other group. Second, this process allowed us to generate a wider range of ideas in a short time, consistent with our contractual timelines.

A series of feasible design concept variations emerged. Concept 1 (Figure 2) required a balancer-module (spring) to be fixed to the torso (lower end), where a cable extended upwards to an attachment on the helmet. The posterior of the helmet (upper end) was also fitted by means of a track system that allowed the attachment to slide in order to accommodate axial rotation. Additionally, the body mounted balancer module allowed the user to directly increase or decrease the tension in the spring, increasing or decreasing the counter-balancing moment.

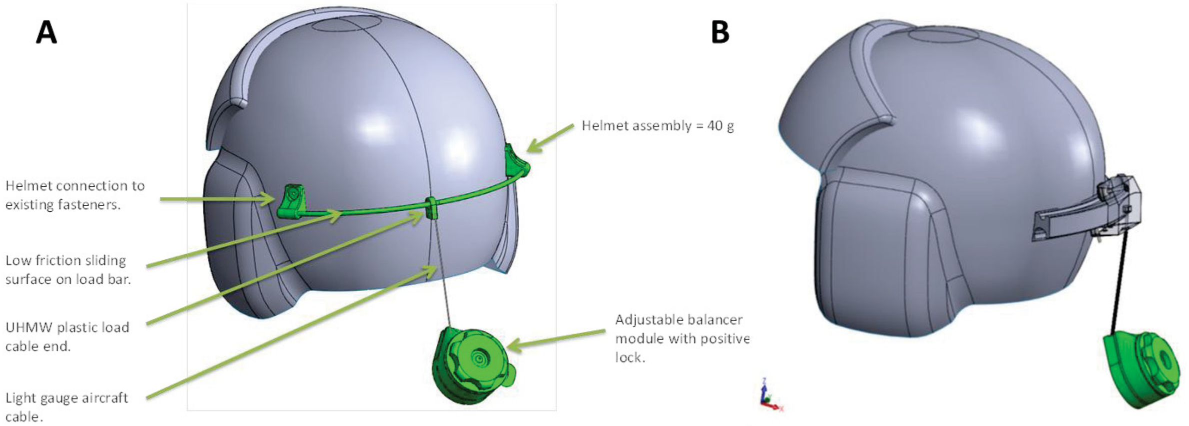

Figure 2 – Design Concept 1 – Torso mounted force adjustable balancer with a helmet track system from (A) rear and (B) side.

Concept 2a (Figure 3) also required the spring component to be fixed to the torso, where a cable extended upwards to a fixed attachment on the helmet. The attachment on the helmet also contained two key features: a quick release to disengage the spring, and a lever that allowed the user to alter the moment arm of the spring force. This mechanism allowed the user to directly increase or decrease the moment arm, increasing or decreasing the counter-balancing moment, without increasing the force in the spring.

Figure 3 – Design Concept 2 – Torso mounted, moment adjustable balancer with a quick release mount. The box containing the spring mechanism (lower attachment point) can also be increased to contain the batteries (Design Concept 2b), reducing the weight and inertia of the head-helmet system even further.

Concept 2b was a derivative of 2a. Where concept 2a required the spring mechanism to be contained in a box on the torso (lower attachment point), concept 2b provided additional space beside the mechanism to accommodate the batteries required to power the NVGs. In principle, concepts 2a and 2b function identically; however, 2b allowed for the batteries to be removed from the helmet, further reducing the head-borne mass.

Design Concept 3 (Figure 4) emerged afterwards as a hybrid of the previous designs. In Concept 3, a force adjustable spring (from Concept 1) could be mounted directly to the helmet with a quick release mechanism (Concept 2), that is attached to a track system (Concept 3).

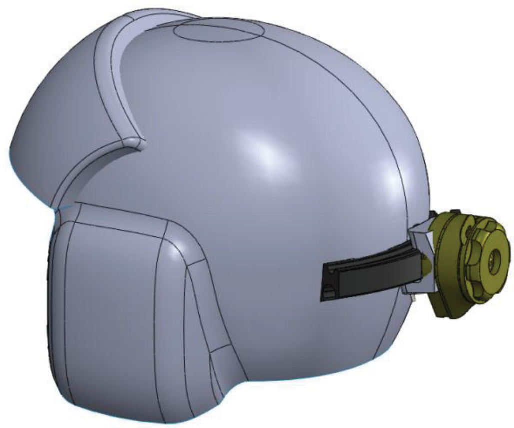

Figure 4 – Design Concept 3 – A hybrid of the initial two design concepts where a force adjustable spring is mounted directly to the track system on the helmet.

1.3.4 Select Concept

The intent of this stage was to conduct preliminary evaluation and verification exercises that would help the design team measure the performance of the central concept (spring-based counter balance system) and test each of the concept variations. Quick, simple pilot studies were conducted to help address specific design questions such as: "how long does the cable need to be?" (Annex B) and "Can users feel an appreciable change in the device when adjusting the moment arm" (Annex C) that emerged early in the process. With preliminary prototypes designed and developed using 3D printing rapid prototyping technology, the team moved forward to a more targeted set of evaluations including a field test and lab-test as described in more detail in Section 3. These data were used, in concert with the design specifications in order to select the preferred concept. A general summary is provided in Table 1 (page 7).

1.3.5 Refine Concept

The intent of this phase is to further refine the selected concept into a production ready product. Within the timelines and scope of this project a production ready prototype has not yet been developed. However, considering the data generated through lab and field testing, two elements of the concept need further refinement before a production ready device is developed. Firstly, while the current track system allows for rotational motion, there are limitations with the current design that are still imposing a minor imposition when moving the head side to side (particularly so when also adopting a forward flexed position). Additionally, as is expected with rapid prototypes, wear and tear is an issue. Through refinement, the device needs to be modified to continue efforts to reduce friction points and to incorporate robust, yet inexpensive materials that will limit wear.

Table 1 – Matching design concept performance to functional specifications.

Design Parameters	Helmet Based Counter-Weight (existing system)	Concept 1	Concept 2a	Concept 2b	Concept 3
Reduce the total mass on the head	✗	✓	✓	✓ ✓	✓
Lower the inertia of the system	✗	✓	✓	✓ ✓	✓
Reduce the muscular demand	???	✓	✓	✓	✓
Reduces overall neck compression	✗	✓	✓	✓	✓
Accommodates head rotation	✓	✓	✗	✗	✓
Variable/adjustable off-load	✗	✓	✓	✓	✓
Easy/Quick to remove	✗	✗	✓	✗ *	✓
Low intrusion on environment	✓	✓	✓	✗ *	✓
Robust	✓	✓	✓	✓	✓
Low-cost	✓	???	???	???	???

✓ Indicates that current design meets the stated specification

✗ Indicates that current design meets the stated specification

??? Unknown

* Requires a deeper analysis to understand the impact of battery removal from helmet

2 Biomechanical Analysis

2.1 Intended Purposes for the Model

The purposes of the simplified 3D biomechanical model are:

a. to evaluate the static moments and forces for the current system for: (i) head only, (ii) head + helmet, (iii) head + helmet + NVG + batteries, and (iv) head +helmet + NVG + CW + batteries;

b. to determine the magnitude of spring force needed to counterbalance NVG with and without the battery pack. The counterweights (CW) on the helmet would be removed; and,

c. to re-evaluate the moments and forces when compared to the (i) head only, (ii) head+helmet, (iii) head+helmet+NVG) and the two prototype conditions, namely: (iv) head + helmet + NVG + new counter-measure device (no batteries), and (v) head + helmet + NVG + new counter-measure device (with batteries).

2.2 Assumptions and Limitations of the Models

There are several assumptions and limitations to the model. These include but are not limited to:

a. estimation of head and neck physical properties based on the scientific evidence as reported by Yoganandan et al. (2009);

b. estimation of moment arm lengths from estimated centres of mass (CoM);

c. development of a static 3D biomechanical model since we did not have a complete set of physical properties of the helmet and its accessories for a dynamic 3D model; and,

d. The head-only 3D static model was a reasonable determination of 3D moments at the level of the occipital condyles rather than the complete cervical spine.

e. A first generation 3D dynamic model was developed and considered a reasonable estimation of T1 forces and moments to encompass full neck motions. In this report it is used for comparative purposes of flexion/extension moments only.

Despite these limitations, we are confident in the static model for several reasons. Many of the errors would be systemic across all conditions. For example, the moment arm lengths may be incorrect; however, this would be true for all conditions. In addition, the postures assumed are primarily static in nature with many small slow movements; hence, a static 3D model is probably a realistic representation of the moments and forces experiences by aircrew members. Finally, the analyses were conducted over a range of motion (ROM) indicative of motions at atlanto-occipital joint (C1-head), atlanto-axial (C1-C2) joints only; this would limit errors that could occur due to calculations for the full cervical spine.

2.3 Second Generation Multi-Body Model

A more sophisticated biomechanical model of the head-neck complex was created using Altair MotionSolve (Figure 5). The head, cervical vertebrae and helmet system were created corresponding to general geometry provided by DND, literature and the National Crash Analysis Centre, Hybrid III dummy finite element model (used for cervical vertebrae geometry). The model was created using stacked revolute joints for each of the vertebral joints, with T1 being considered fully constrained. The remaining segments allowed head flexion and extension, as well as rotation (yaw), however inversion/eversion (lateral bending) was not considered. The motion of the head was driven using applied motion functions to each of the joints, with the overall motion of the head attributed to the cumulative motion of the joints. This model allows improved calculation of the head displacement with respect to T1 at various articulations, captures of dynamic effects, and allows integration and evaluation of various countermeasures. The multi-body dynamics model includes mass-inertia effects, and was used to evaluate the various input conditions and potential countermeasures.

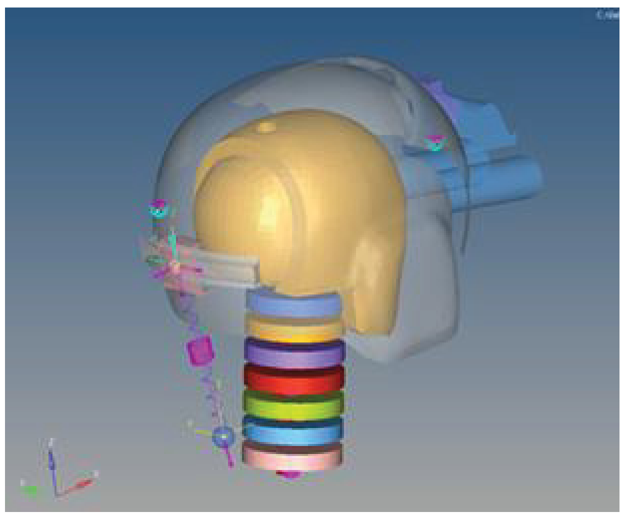

Figure 5 – First iteration of a multi-body dynamic model that includes the neck segments.

2.4 Input Parameters to the Model

The first task in developing a biomechanical model is to determine how one wishes to model the head and neck complex so that one can apply appropriate masses, and other physical properties. Figure 5 is a picture of the complete cervical spine and includes the head. Yoganandan et al. (2009) conducted an extensive review of the physical properties of the human head. Based on the reported studies in this article, we selected data from Walker et al. (1973) as inputs to the biomechanical model because these researchers separated the physical properties of the head from the neck (see blue lines on Figure 6). This point of separation allowed us to assume an average head mass of 4.46 kg with a known centre of gravity at the upper edge of the ear canal. Also depicted on Figure 6 are the x, y, and z axes of rotation. If the head is bent laterally to either side,

this motion is about the x axis. If the head is flexed or extended, this motion is about the y axis. If the head is rotated to either side, this motion is about the z axis.

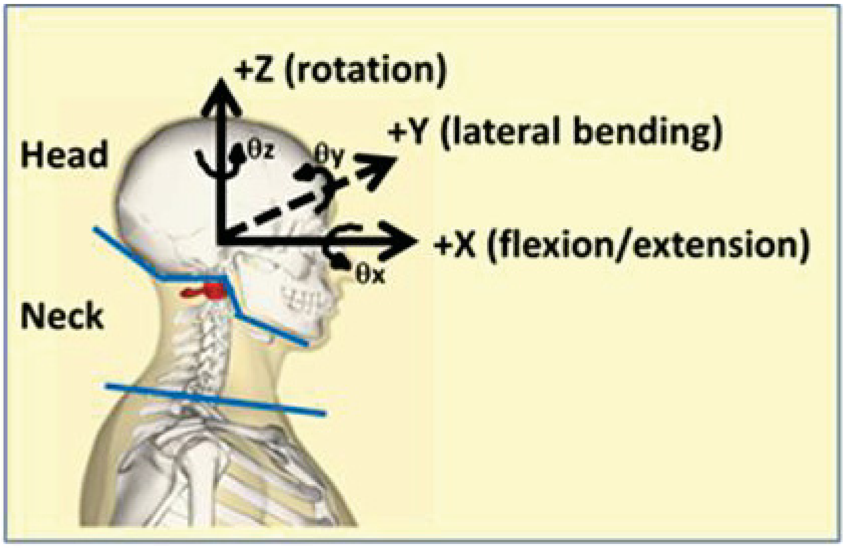

Figure 6 – The cervical spine is comprised of 7 vertebrae with the atlas (C1) and axis (C2) depicted in red. The blue lines denote the separation between the head and the neck. The axes of rotation used for the biomechanical model are: x = lateral bending; y= flexion/extension and z = rotation. The head's centre of mass is located at the ear canal's upper edge.

A three-dimensional inverse static model was developed in MatLab to estimate the net moments and forces acting at the occipital condyles (OC) when simulating different head-helmet systems configurations for Canadian Forces (CF) aircrew. The OC is commonly used in the crash testing industry as the point about which moments and forces are calculated (King, 2000). This model was developed to estimate kinetic variables when simulating the effect of different head and helmet system configurations as the head moved through a range of flexion/extension (-10° extension to +40° of flexion), axial rotation (-40° rotated to the left to +40° rotated to the right) and lateral bending (-40° rotated to the left to +40° rotated to the right) in 1° increments. These ranges of motion are reasonable estimates of the head motion that takes place at either the atlanto-occipital (C1-head) joint for flexion and lateral bending or between atlanto-axial (C1-C2) joint for axial rotation.

The mass and location of the head centre of gravity (CoG) of the head relative to the OC was extracted from data published by Yoganandan et al. (2009 – see Table 17). The remaining item masses were obtained from data provided to us through our scientific authority based on data collected at Canadian Forces Base Valcartier. The CoG locations of these items were based on our previous report (Fischer et al. (2013) called "Near-term ideas to address helmet systems-induced neck pain" (DRDC Toronto CR 2013-039 – Figure 6) and were corrected to reflect lengths from the atlanto-occipital origin. All input data are reported in Table 2.

Table 2 – Mass and centre of gravity (CoG) location information used in the biomechanical model.

Item	Mass (kg)	Lx (m)	Ly (m)	Lz (m)	Notes
Head	4.46	0.0178	0	0.0531	Table 17 - Yoganandan et al 2009
Helmet	1.4956	0.0128	0	0.1231	CFB Valcartier and previous report
NVG	0.6006	0.1861	0	0.072	CFB Valcartier and previous report
Batteries	0.3417	-0.1477	0	0.1207	CFB Valcartier and previous report
CW	0.9017	-0.1477	0	0.1207	CFB Valcartier and previous report

*Lx, Ly, Lz refer to the item's centre of gravity location in along the x-axis (anterior/posterior), y-axis (medial/lateral), and z-axis (superior/inferior) with respect to the occipital condyles. Mass data were collected at CFB Valcartier and CoG lengths (Lx, Ly, Lz) were taken from our previous report.

2.5 Purpose 1: Examining the Current Helmet System

Using these inputs, static 3D moments about the OC point were calculated, in addition to the estimated reaction compression and shear forces that would be expected. It is important to note that the estimated compression and shear forces do not represent the estimated bone-on-bone forces as the contribution of internal force generating elements (e.g., muscles and other soft tissues) have not been modeled here. Rather, the model simply represents the expected contributions from these external sources (e.g., helmet, NVG, batteries, counterweight). Forces and moments were calculated for four different cases:

1. Head only (Black solid line)
2. Head and Helmet (Blue dash-dot line)
3. Head and Helmet and NVGs and Batteries (Red solid line)
4. Head and Helmet and NVGs and CW (Magenta dashed line).

Throughout this section, results of moment and forces and their interpretation will be presented in the following order: flexion-extension (FE), lateral bending (LB) and, when appropriate axial twisting. All data will be presented in graphic form based on appropriate ranges of motion at the OC location.

2.5.1 Analysis of Moment Loading at the Occipital Condyles

The model was applied to estimate moment loading at the OC point of rotation in all three principle directions. In pure flexion of the head-helmet system, an extensor moment is needed to counterbalance the flexor moment. For example, when pilots flex their necks forward, the extensor muscles at the back of the neck must contract to counterbalance the flexor moment. In axial rotation (looking left and right), no axial reaction moment is created because the head and

helmet forces are normally perfectly balanced on the left and right sides; as a result, the axial moment is zero because the forces act directly through the OC centre. However, when one turns one's head-helmet system from side to side, a lateral moment is created. For example, if a pilot looks to the left side, it creates a lateral bending moment to the left because the NVG are rotated to the left side. This action must be counterbalanced by muscles acting on the right side of the neck. To demonstrate the moments required under each condition, a series of figures are shown below.

Figure 7 is a 3D illustration of the moment about the flexion-extension (FE) axis as a function of both neck flexion and axial rotation based on a standard day-time helmet configuration (Head+Helmet – Case#2). The FE moment gradually increased with increased neck flexion and it was largest (~3.3Nm) when the neck was flexed to 40° and almost non-existent at -10° in extension. When axial twist from -40° left to +40° right is simultaneously shown, it had little effect on the FE moments, regardless of FE angle. These data highlight that flexion-extension movements are the principle driver of FE moment magnitude. Hereafter in this report, only the FE motions will be shown for each helmet condition.

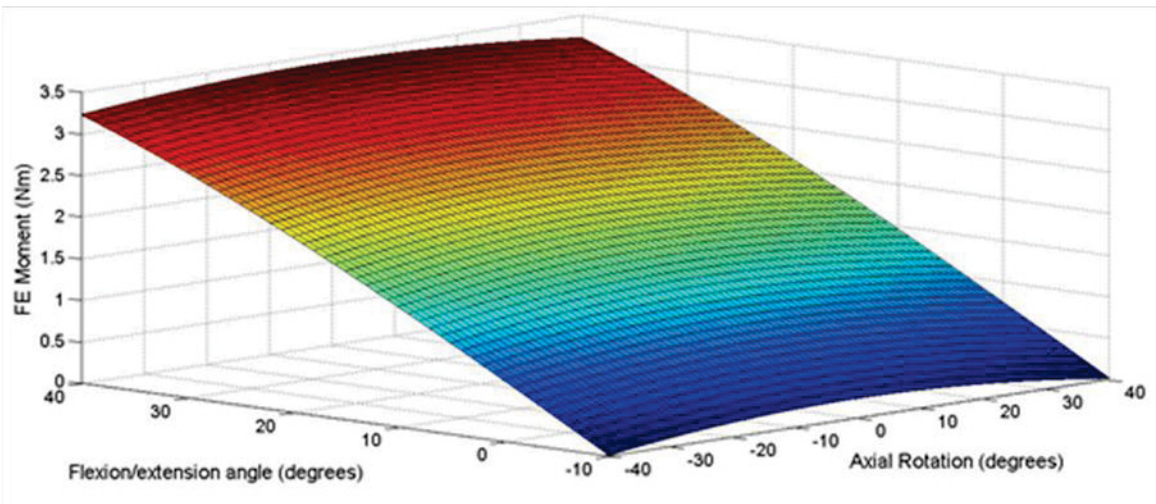

Figure 7 – The Flexion-Extension (FE) moment as a function of neck flexion and axial rotation angles at the OC point of rotation. These data are based on the standard day-time head + helmet configuration. FE moment magnitude is primarily a function of the neck FE angle.

Figure 8 illustrates the moment about the lateral bend (LB) axis as a function of both neck flexion and axial twist motions based on a standard day-time helmet configuration (Head + Helmet – Case 2). The LB moment is negligible at 0 ° of axial rotation; however as the head-helmet was rotated to the left (-40°) the LB moment rose to ~0.7 Nm with the same LB moment created as the head was rotated to the right (+40°). When flexion-extension motions were considered, there was no effect on the LB moments. Hence, axial (side-to-side) motions were the principle contributor to the LB moments motions. Hereafter in this report, only the axial motions will be shown for each helmet condition.

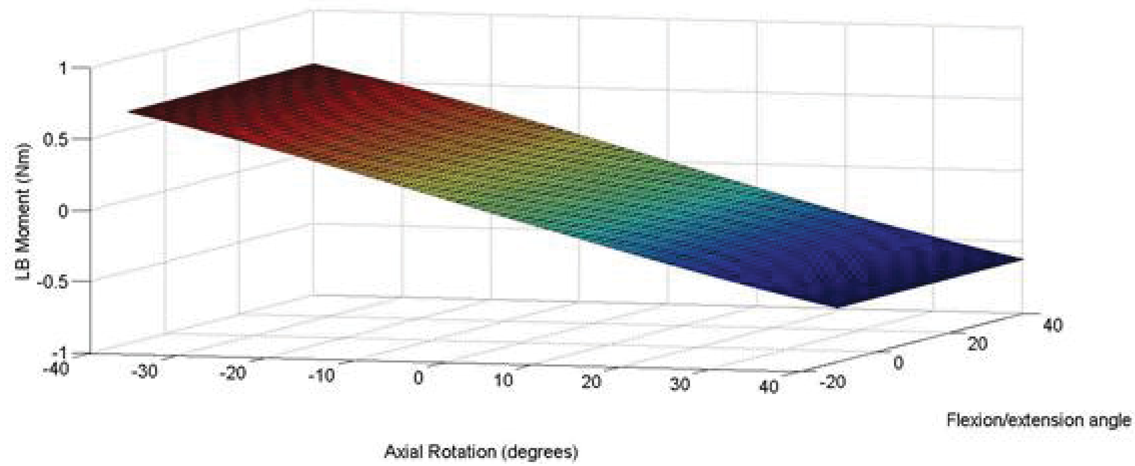

Figure 8 – The Lateral Bend (LB) moment as a function of neck flexion and axial rotation angles at the OC point of rotation. These data are based on the standard day-time head + helmet configuration. LB moment magnitude is primarily a function of the neck axial rotation angle.

2.5.2 Analysis of Moment Loading based on Testing Configurations

Now that we have shown that the flexion-extension movements are the primary contributor to FE moments and axial rotation movements are the primary contributor to LB moments, the various head-helmet configurations will be compared about single axis motions only. In each of the following graphs, the head alone (case #1 - black) and the head + helmet (case #2 - blue) can be used as a benchmark against which the NVG + batteries (case #3- red) and NVG + batteries + CW (case #4 - magenta) can be compared.

In Figure 9, all FE moments occurred at the largest flexion angles of 40° with the worst situation being case #3 (red) at 4.3 Nm followed closely by case #4 (magenta) at 4.1 Nm. Use of the counterweight with the NVG (case #4) does have a small influence when the neck flexion angles are small; however, its effectiveness deteriorates rapidly the further the head is flexed forward. This could be one of the reasons some pilots and flight engineers do not bother using the counterweight.

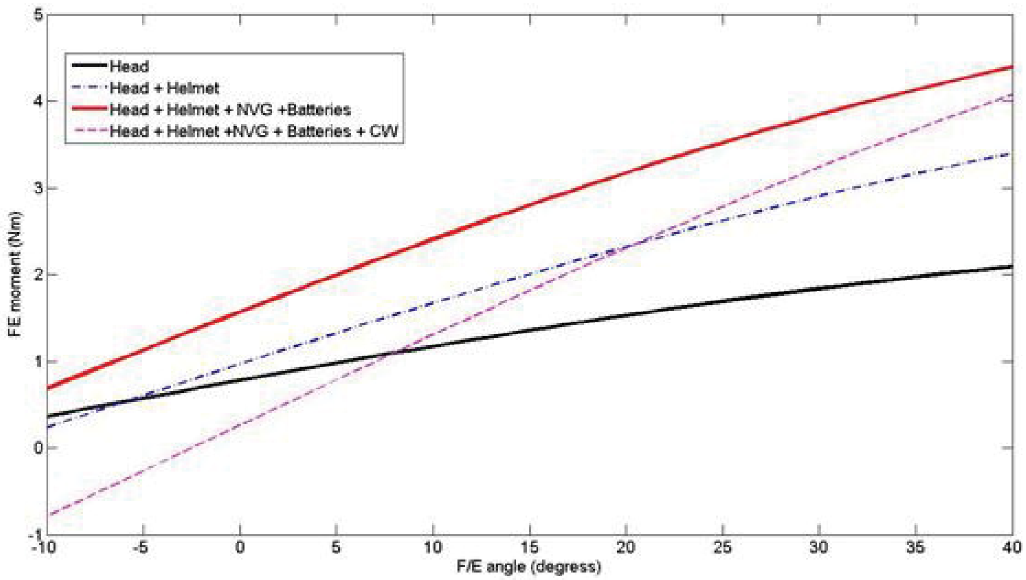

Figure 9 – Flexion-Extension (FE) moment at the neck as a function of the neck FE angle at the OC point of rotation. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend.

Figure 10 illustrates the LB moment as a function of the axial rotation angle and based on different configurations. Overall, the magnitude of the LB moment is low within the typical neutral range of likely positions (+/- 15°). However, when the head is turned to the left or right more dramatically (±40°), the most heavily loaded condition of NVG and counterweight (case #4 – magenta), the muscles on the opposite side to the motion must provide a counter moment. Since head rotation can occur through ~105° in each direction (Nordin and Frankel, 2001), the LB moments will rise even higher with increase neck rotation, especially when dynamic forces, such as accelerations, are also considered.

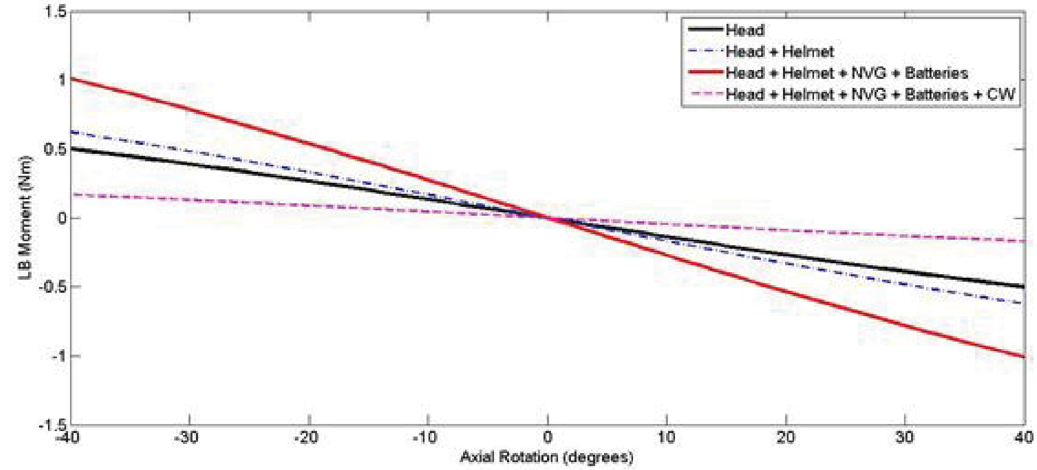

Figure 10 – Lateral Bend (LB) moment at the neck as a function of the neck axial rotation angle at the OC point of rotation. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend

2.5.3 Compression and Shear Loading at the Occipital Condyles

External reaction compression and shear forces were estimated using the model. These loading variables are not an estimate of the actual bone-on-bone forces that are likely to be experienced as they ignore all internal contributions (i.e., muscles, ligaments, tendons, etc.). It is likely that the actual bone-on-bone forces would be increased with an increase in the reaction forces, or alternatively decreased with a decrease in the reaction forces. Figure 11 illustrates the reaction compression forces expected in each of the four different head-helmet system configurations. As the mass increases, so too does the resulting compressive force.

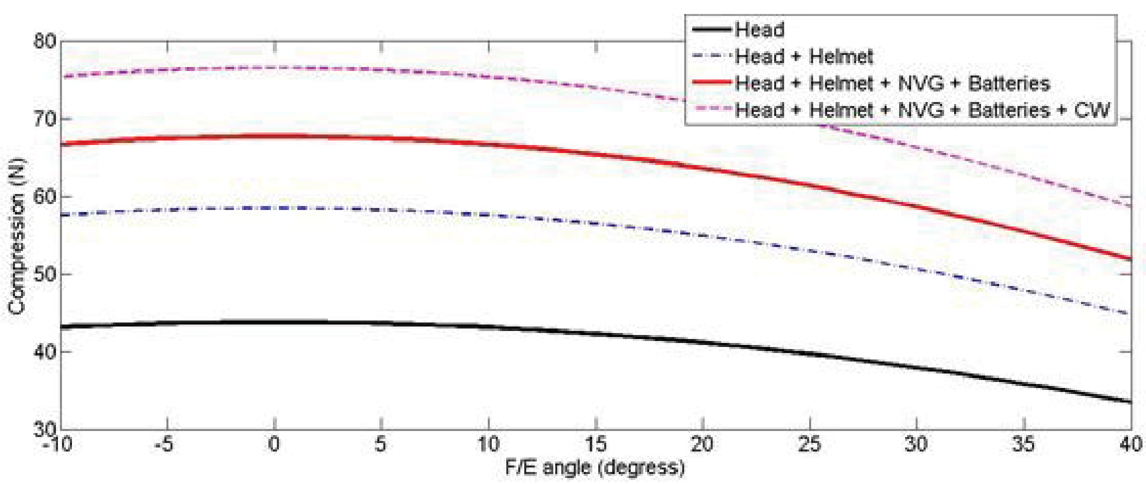

Figure 11 – Reaction compression (N) as a function of the neck flexion angle. Each line indicates the estimated moment based on different head/helmet systems configurations.

In contrast, shear forces in the anterior-posterior direction are ~0.0 N when the centre of mass is directly over the OC (Figure 12). However, the effect of the mass begins to have a more appreciable effect nearer the end range of motion.

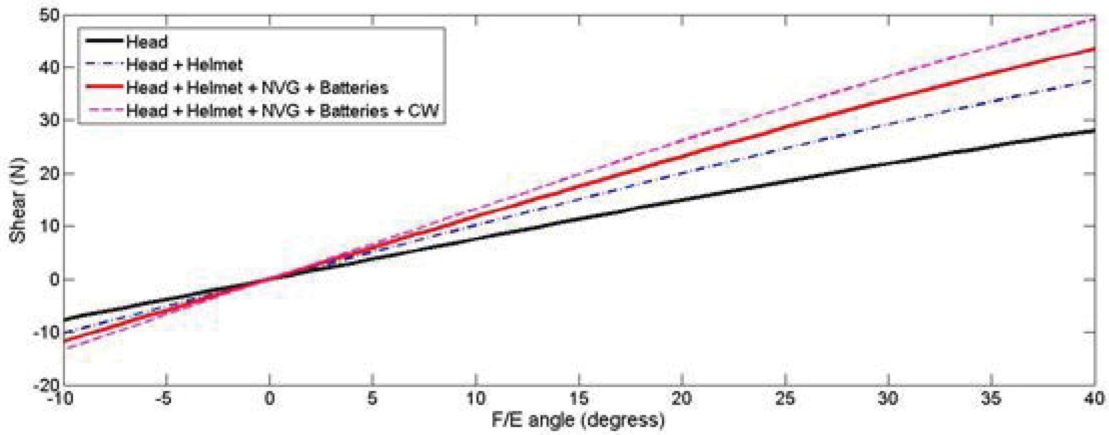

Figure 12 – Reaction anterior-posterior shear (N) as a function of the neck flexion angle. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend.

2.6 Purpose 2: Estimating the Required Restorative Force

2.6.1 Design Concept for Helmet Assistive Device

The design concept for the engineering-based new counter-measure device (termed "Heads-up" through the following illustrations) is to use a spring element to create a restoring force that can be applied to the back of the helmet in order to help counter the effects of the force of gravity acting on the NVGs place on the front of the helmet. This method is an advance over the current CW approach for two reasons: 1) it lowers the overall mass and moment of inertia of the head-helmet system; and, 2) it provides a restoring force that is not gravity dependent. However, there is also the potential to have the spring force reduce the helmet system even further by removing effect of the batteries' mass and moment of inertia. Hence the next section will address the impact of two conditions: a batteries-on model and a batteries-off model.

The next step is to estimate the amount of restoring force to apply via the spring element. The final approach requires that the new counter-measure prototype provide enough restoring force to balance the NVG system such that the resultant moment about the neck is equivalent to the moment experienced without the NVGs. Despite a desire to balance the moments completely, differences in helmet masses and CoG, methods of wearing the helmet, and flight crew head movements all require some effort by the muscles of the neck. Although some individuals may worry about de-training if neck muscles have less demand, this is unlikely given the need to support the helmet's mass and motions required by the flight crew.

2.6.2 Methods

Two scenarios were developed to calculate the restorative force needed in the new counter-measure device (HeadsUp) to counterbalance the NVGs. The first strategy was with the battery pack remaining on the helmet but counterweight removed, and the second involved removal of both the battery pack and counter weight removed from the helmet. In both cases, the gold standard was the restorative force needed to balance the head+helmet only (Case #2). For this analysis, the restorative force values were assumed to be in the range of 0-15 N and the line of action of the Heads-up device (from vertical) was constrained to a range of 0° to 20° of flexion. This range of action covers the expected range of motion possible at the occipital-atlanto and atlanto-axial joints. The point of application of the restoring force remained constant (-0.1477, 0.0, 0.025 – relative to OC). This point was assumed to be in line with the CoG of the battery pack along the horizontal (anterior/posterior) axis, and at the approximate lowest point on the back of the helmet along the vertical (superior/inferior) axis.

For each degree of flexion, the restorative force (N) was calculated for the gold standard (head and helmet) and the two design scenarios (battery-on and battery-off) with the CW removed in both scenarios. Then, an optimization approach was used to determine the optimal required restorative force associated with each line of action for each new counter-measure design scenario when compared to the gold standard. The approach used was to determine the root mean square error between the gold standard (head and helmet) and each design scenario. By this method, it is possible to see the optimal magnitude of the restorative force at each new counter-measure line of action. These data are presented in 3D graphic form.

2.6.3 Results

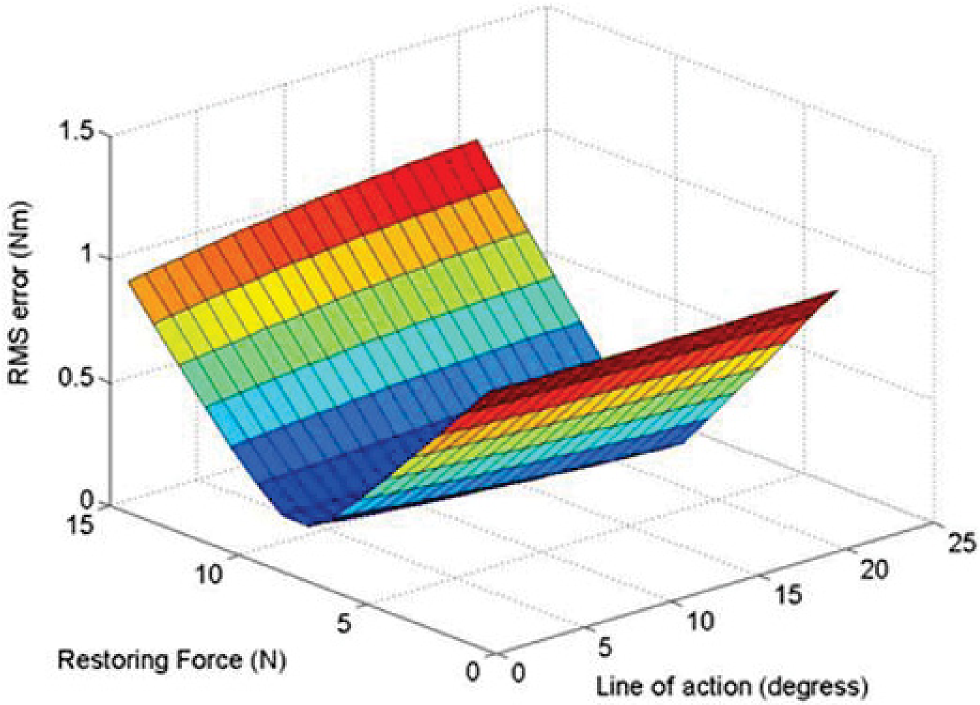

Figure 13 – A surface plot indicating the effect of the restoring force magnitude and the line of action angle on the root mean squared error when applying the new counter-measure device – batteries off prototype model

Figure 13 shows the restorative force needed at associated new counter-measure lines of action when the battery and CW has been removed from the helmet. Regardless of the line of action during head flexion, the restorative force varies between 10 N when the head is vertical to 8 N when the line if action is at 20°. Using these tensions in a New counter-measure prototype will create RMS errors ranging from 0.175 – 0.061 Nm depending on the line of action used. The advantage of removing the battery and CW is that the moment of inertia is deceased as well as the total mass carried. These two factors will reduce the neck muscle force requirement to stabilize and start/stop head motions.

Figure 14 shows the restorative force requirements at associated lines of action when the battery only is left on the helmet/NVG. This design approach will lower the of restorative force requirement to approximately 6 N; however, the minimum RMS errors are increased to 0.258 – 0.205 Nm depending on the line of action used. The RMS error difference means that it will be more difficult to select the correct restorative force when the battery pack is worn on the helmet, all other factors being equal. It also means that the battery pack is still contributing to the added mass (0.3417 kg) and moment of inertia.

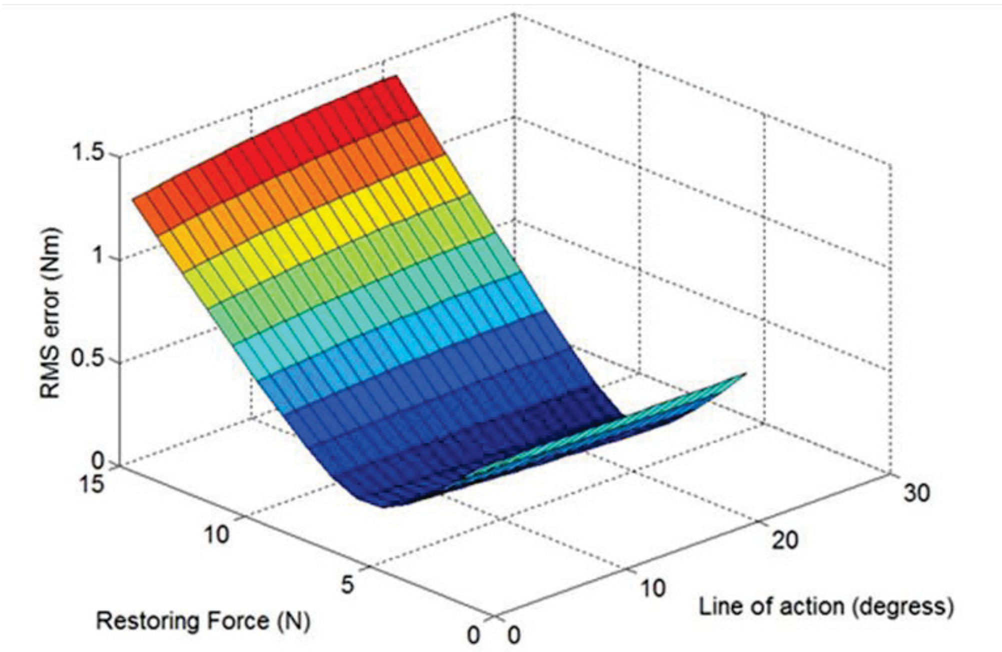

Figure 14 – A surface plot indicating the effect of the restoring force magnitude and the line of action angle on the root mean squared error when applying the new counter-measure device – with batteries on prototype model.

2.7 Purpose 3: Evaluation of New Counter-Measure Design Concepts

The next step in the analysis was to determine the impact of the optimization outcomes for the new counter-measure design scenarios (with and without batteries on the helmet). For this analysis, the model was adapted to assume a fixed restorative force at a fixed angle from the vertical. For the new counter-measure – no batteries model, the restorative forces was assumed to be 8 N acting at an angle of 13° from vertical. For the new counter-measure – with batteries, the restorative force was assumed to be 6 N, again acting at an angle of 13°. To evaluate the anticipated benefit the following cases were examined.

- Head only (Black solid line)
- Head and Helmet (Blue dash-dot line)
- Head and Helmet and NVG and Batteries (Red solid line)

- Head and Helmet and NVG and New Counter-Measure (Green starred line)

Since the gold standard is considered Case #2 (head and helmet), then it is important to determine if the two new counter-measure scenarios (Case #4) compares to the control condition.

2.7.1 Moment Loading at the Occipital Condyles

Based on the review of literature included in our previous report (Fischer et al., 2013), the flexion-extension (FE) moment posed the greatest concern. As indicated in Figure 15, when applying the new counter-measure -no batteries prototype to compliment NVG use, it is expected that the FE moment experienced about the OC will be equivalent to the normal FE moment experienced during day-time flying without NVGs. The new counter-measure-No Batteries (green stars) is a considerable reduction from the moment requirements experienced in the traditional NVG configuration (red line). The shape of the curve is also very similar to the Head + Helmet moment curve (blue dash-dot), unlike the counterweight curve shown in Figure 9.

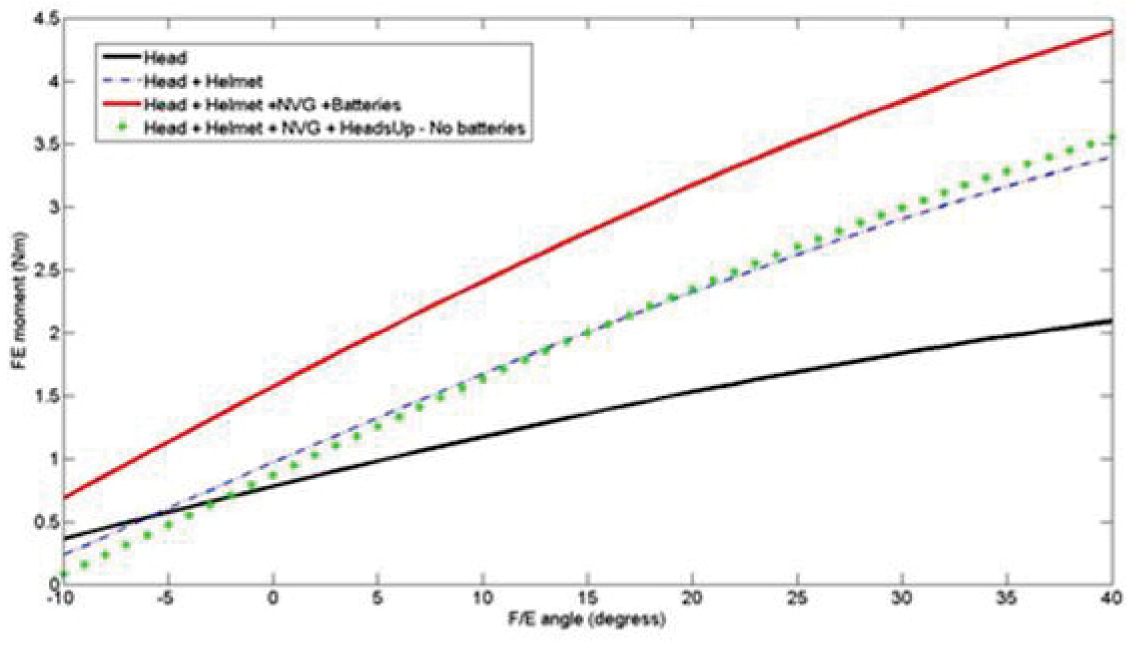

Figure 15 – The new counter-measure device (referred to as HeadsUp) No-Batteries Model. The Flexion-Extension (FE) moment experienced at the OC point of rotation as a function of the flexion/extension angle. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend.

The next step was to examine the effect of leaving the batteries on the helmet (Figure 16). When the batteries are added to the new counter-measure system, its curve (green stars) followed the shape but was ~0.75 N.m less of the CW (red) curve. However, the FE moments were not dramatically reduced. Our advice is to remove as much weight from the helmet as possible since any added weight to the helmet will increase neck forces and moments unnecessarily.

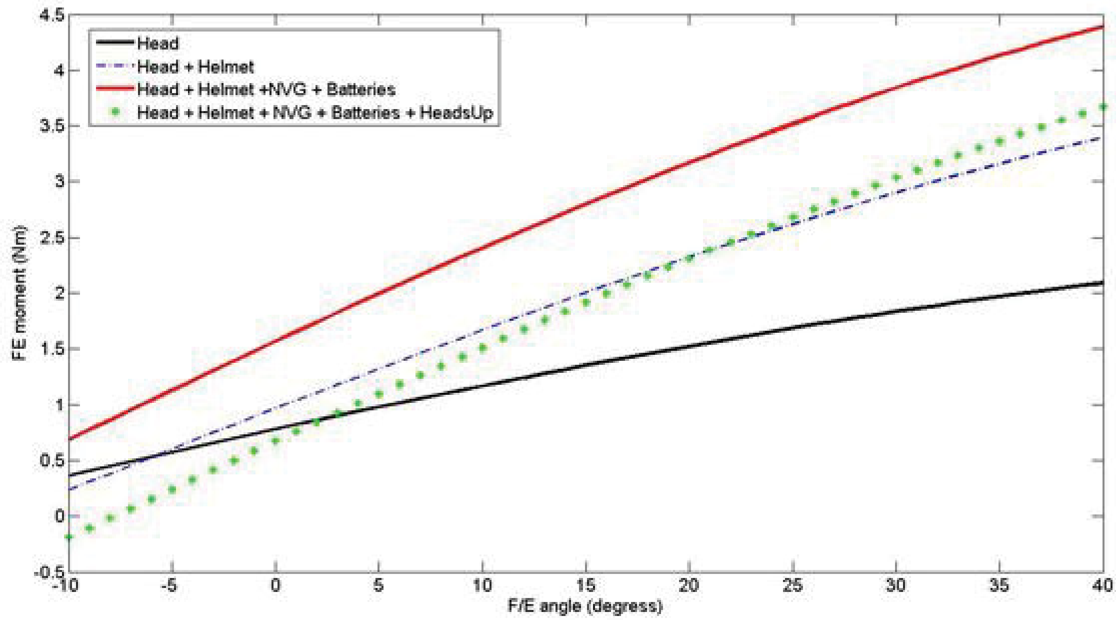

Figure 16 – The new counter-measure device (referred to as HeadsUp) – With Batteries Model. The Flexion-Extension (FE) moment experienced at the OC point of rotation as a function of the flexion/extension angle. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend.

2.7.2 Lateral Bending Moments

While lateral bending moments were less of a concern, Figures 17 and 18 demonstrate the modelled LB moments as a function of the neck axial rotation angle for the new counter-measure -no batteries and new counter-measure-batteries conditions respectively. As can be seen by the graphs (green stars), both designs reduce the required lateral bending moment. When comparing the two conditions, the new counter-measure no battery condition would require half the LB moment of the battery condition because of the reduced mass and moment of inertia.

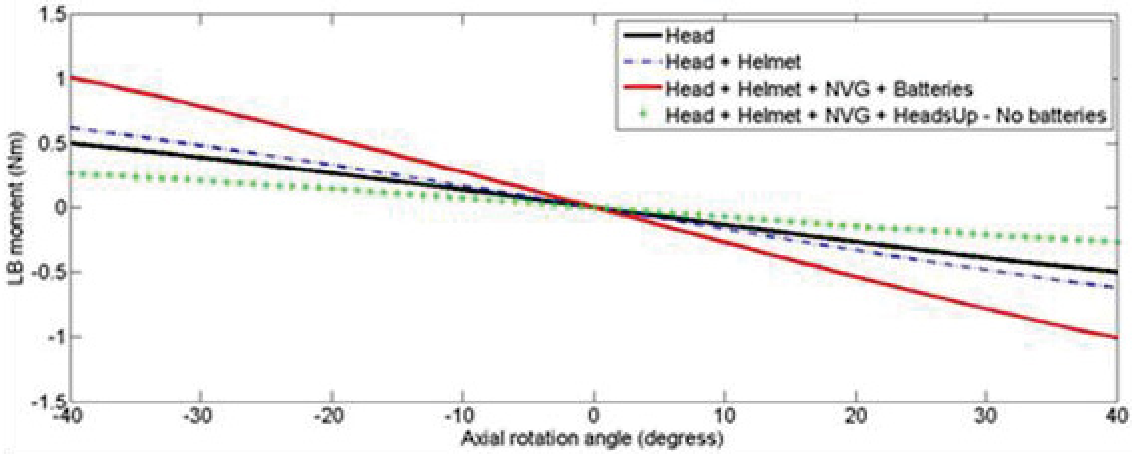

Figure 17 – The Lateral Bend (LB) moment experienced at the OC point of rotation as a function of the axial rotation for the new counter-measure device (referred to as HeadsUp)-No-Batteries condition. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend.

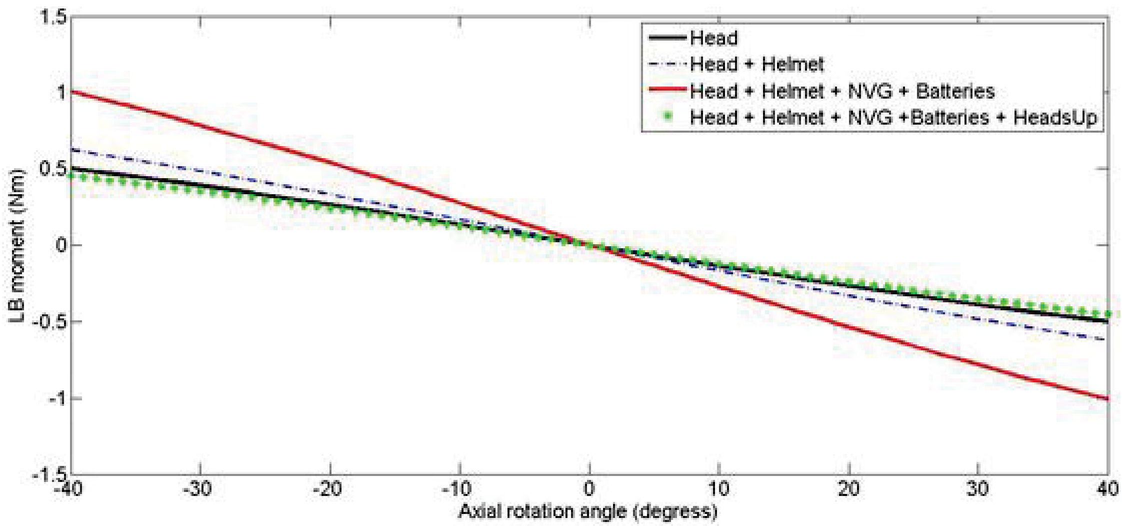

Figure 18 – The Lateral Bend (LB) moment experienced at the OC point of rotation as a function of the axial rotation for the new counter-measure device (referred to as HeadsUp)-Batteries condition. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend.

2.7.3 Twisting Moments

As reported earlier, there is no moment about the twisting axes in the current situation because all devices attached the helmet (NVG, CW, batteries) are centered between the left and right sides of the helmet. However, when using the new counter-measure device, the spring tension will create a horizontal moment due to the horizontal component of its restoring force. This component will

impose an added moment requirement about the axial rotation axis when the head is axially rotated away from neutral. However, as indicated in Figures 19 and 20, this increased moment is modest and almost identical between the new counter-measure-no-batteries and new counter-measure-batteries conditions.

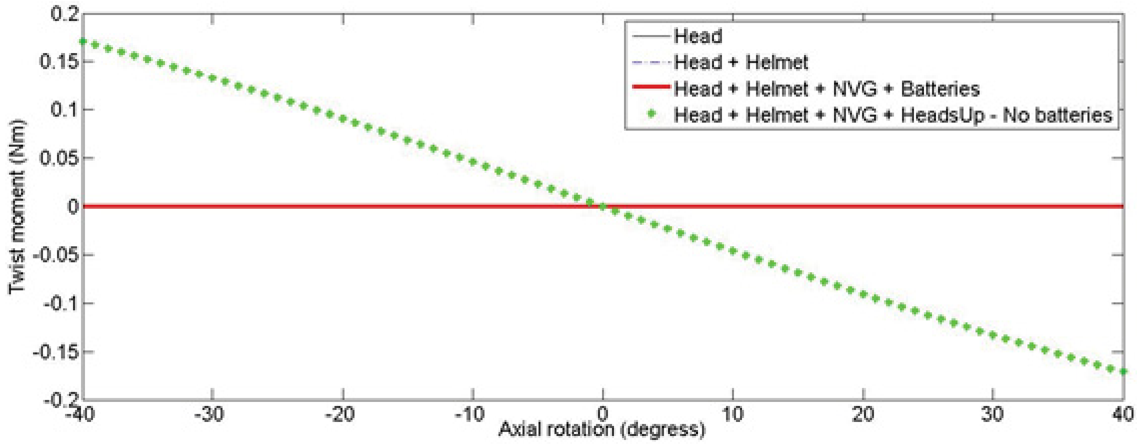

Figure 19– Twist moment during the new counter-measure device (referred to as HeadsUp)-no-battery condition. The axial twist moment experienced at the OC point of rotation as a function of the axial rotation. Each line indicates the estimated moment based on different head/helmet systems configurations. Only the new counter-measure device condition produces forces that result in an axial moment element.

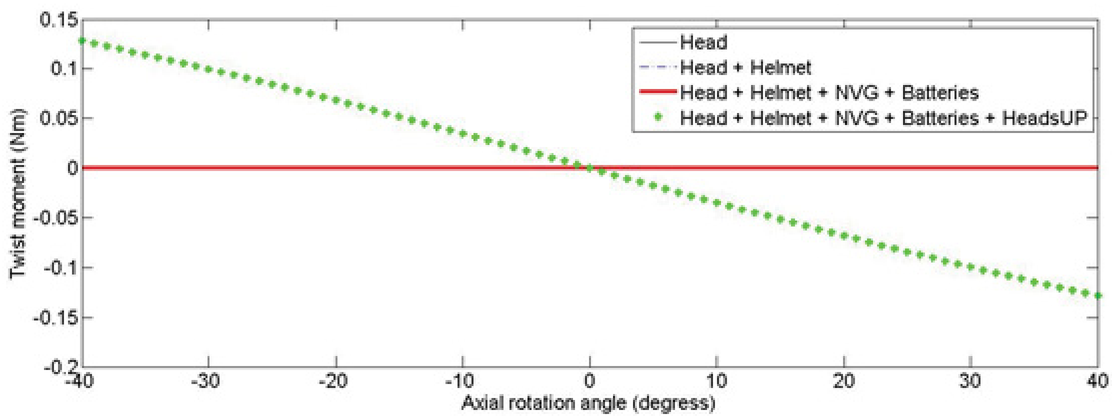

Figure 20 – Twist moment during the new counter-measure device (referred to as HeadsUp)-with battery condition. The axial twist moment experienced at the OC point of rotation as a function of the axial rotation. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend. Only the new counter-measure device condition produces forces that result in an axial moment element.

2.7.4 Compression and Shear Loading at the Occipital Condyles

Reaction compression and shear forces during the flexion/extension motions were again estimated. However, this time the CW was not considered in the analysis but instead, the new counter-measure device prototype. By design the new counter-measure device will add modestly

to the compressive and shear forces. An assumption was made to constrain the line of action of the new counter-measure device restorative force to 13° in the global coordinate system based on the design of the helmet, and how it rotates with respect to OC. Results are provided in Figure 21 (new counter-measure – No batteries) and Figure 22 (new counter-measure Batteries). The new counter-measure – No batteries provides a modest decrease in compressive loading; however the compressive force still remains approximately 12 N (2.5 lbs) greater than the normal head+helmet compressive loading and only 5 N less than wearing the CW. To place these compressive loads in perspective, the magnitudes will be compared to carrying loads on one's head. The compressive force during head carrying tasks among African women averaged 263 N (59 lbs) (Lloyd et al., 2010) and for Nepalese male porters averaged 441 N (99 lbs) (Bastien et al, 2005). By comparison, the compressive force at OC is ~ 70 N (15.7 lbs), which is probably within the capacity of most aircrew members. However, these data can be misleading since the forces on the head can be much more when one considers co-contraction of muscles and accelerations due to vibration. In addition, the main cause of neck pain appears to be cumulative loading over the duration of a mission.

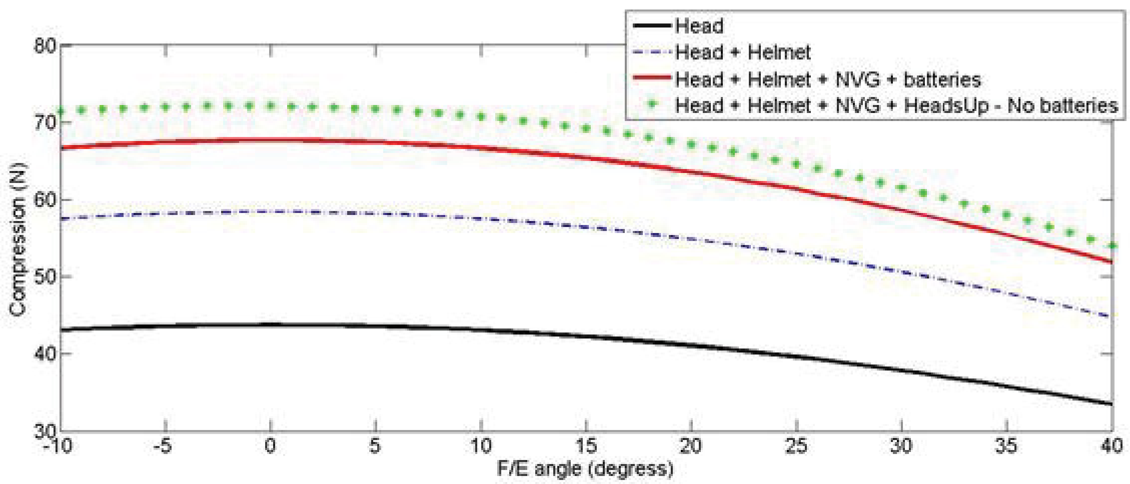

Figure 21 – Reaction compression (N) during the new counter-measure device (referred to as HeadsUp) - no Batteries as a function of the neck flexion angle. Each line indicates the estimated compression force based on different head/helmet systems configurations as described in the legend.

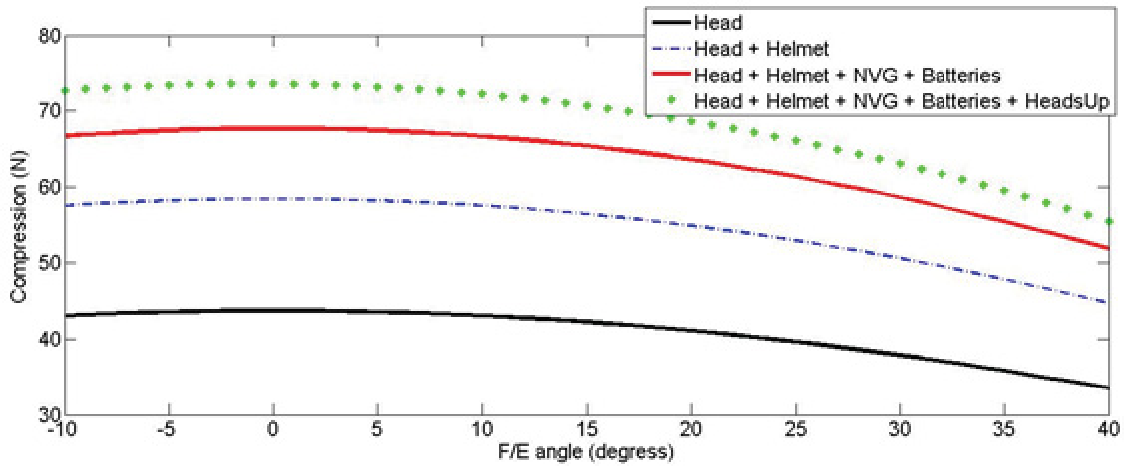

Figure 22 – Reaction compression (N) during the new counter-measure device (referred to as HeadsUp) - with Batteries as a function of the neck flexion angle. Each line indicates the estimated compression force based on different head/helmet systems configurations as described in the legend.

When anterior-posterior shear loading was considered for the new counter-measure -no batteries (Figure 23) and the new counter-measure -with batteries (Figure 24), the results do not differ from the CW condition as shown in Figure 12. In all cases, the shear forces increase with increase neck flexion. There are only marginal differences in anterior-posterior shear loading that is experienced between the helmet system conditions. Based on a biomechanical model that used EMG of maximal isometric contraction, Monorey et al. (1988) found that the maximum anterior/posterior shear force were 135 N on the C4-C5 level. Although not at the same location in the cervical spine, it is doubtful that shear forces would exceed capacity under any of these conditions. But one must consider the impact of duration for these levels of shear forces.

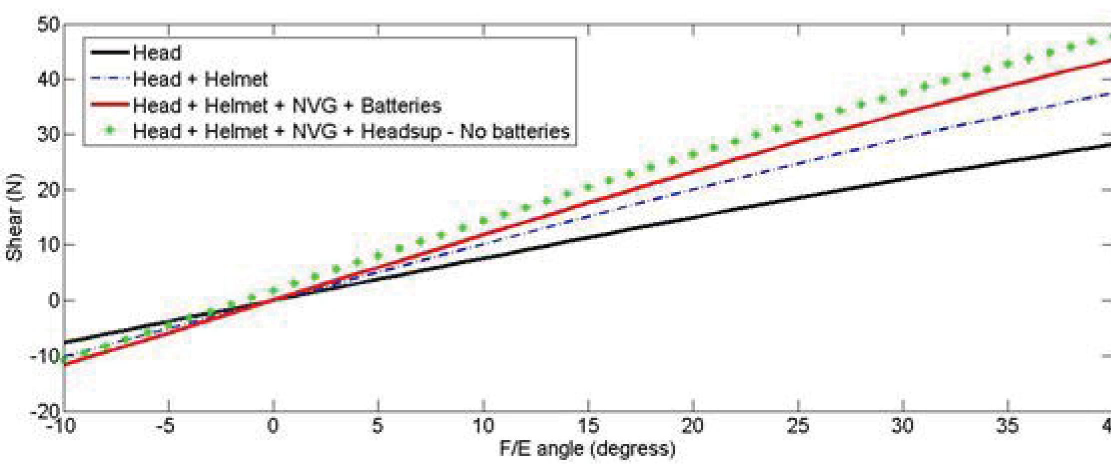

Figure 23 – Reaction anterior-posterior shear (N) during the new counter-measure device (referred to as HeadsUp)-no batteries condition as a function of the neck flexion angle. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend.

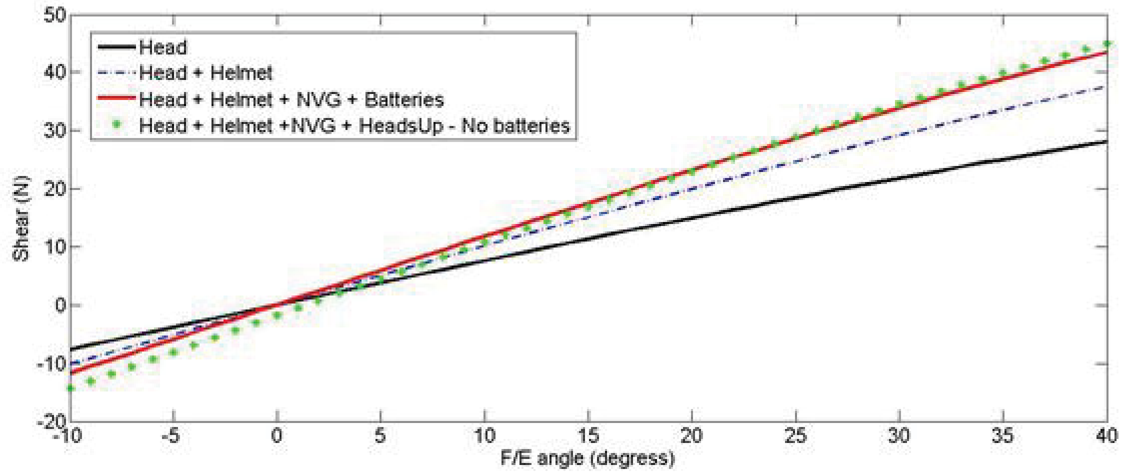

Figure 24 – Reaction anterior-posterior shear (N) during the new counter-measure device (referred to as HeadsUp)-with Batteries condition as a function of the neck flexion angle. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend.

2.8 Preliminary Review of 3D Dynamic Model

As mentioned in Section 2.3, a first generation 3D dynamic model was developed to create a fully dynamic head and 7 segment neck model. This model will eventually allow us to calculate the moments and forces about the C7-T1 joint. But the first step in the analysis is to compare the static model to the dynamic model at the atlanto-occipital joint. This was done for FE moments only. Future work will involve comparing all 3D static forces and moments to 3D dynamic forces and moments for verification purposes.

Figure 25 should be compared to Figure 9. Please note that these figures are upsidedown to one another because different conventions were used (i.e., referenced opposite at OC point). Based on Figure 25, the Head+Helmet+NVG+CW+batteries (Case 5 blue line) resulted in the highest moment at 40° of flexion (~ 4.3 N.m) at the atlanto-occipital joint. This is also true for the static model. Similarly, the head only (Case 1 – yellow line) had the least moment at ~1.2 N.m at 40° of flexion for both the static and dynamic models. Other curves were also similar between the two models based on a visual comparison.

To further compare results of the static and dynamic moment, one situation (Case 4 – Head+helmet+NVG+battery pack) was compared across FE moments from -10° of extension to 40° of flexion (Figure 26). For Case 4, the static data (red hashed line) was compared to the dynamic data (green solid line). Other than a hiccup in the graphing algorithm around 0º to -10º, the curve shapes between the two methods of calculation were quite comparable. Further analysis of this comparison between the Matlab code and the MotionSolve program will be completed in the next phase.

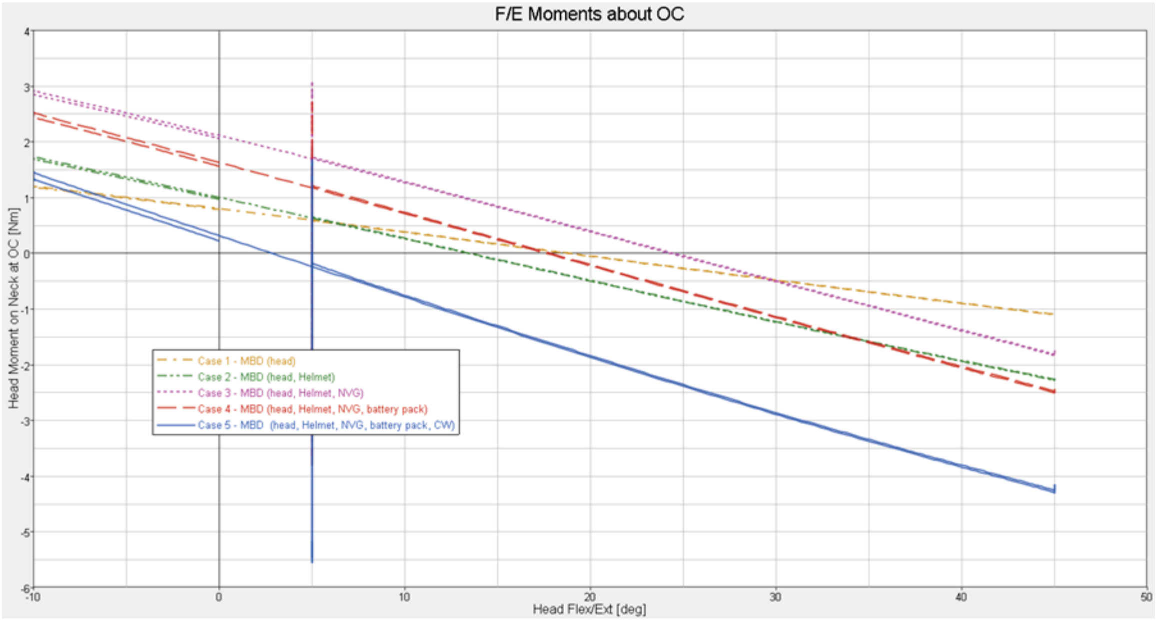

Figure 25 – Results of MotionSolve method of calculating FE moments for the various conditions using the current systems. These results can be compared to Figure 8 which was calculated using a custom Matlab program. Note: different conventions were used thus inverting the y axis.

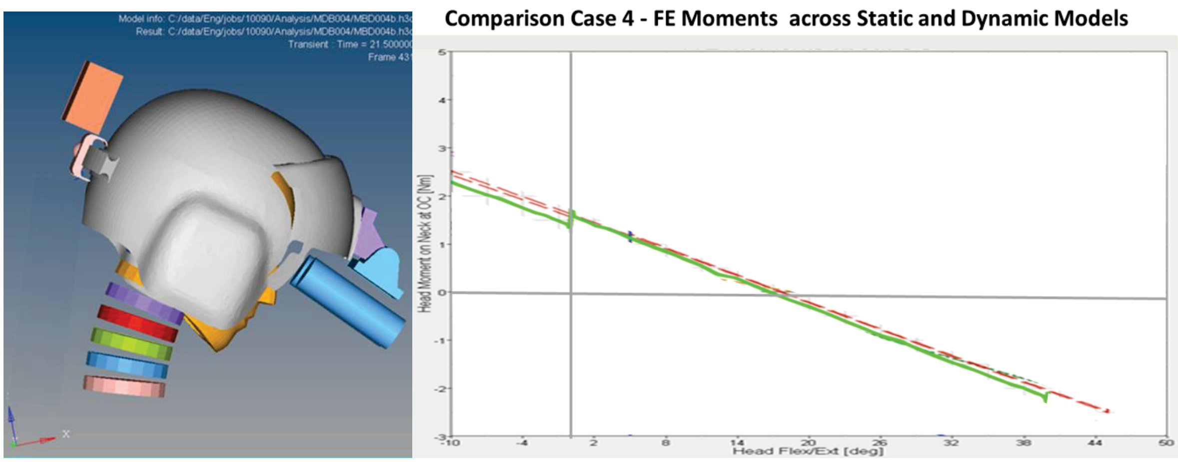

Figure 26 – A comparison of FE moment calculations between the static (red hash line) and the dynamic (green line). These data had comparable input constants but different software (Custom MatLab vs MotionSolve).

2.9 Biomechanical Analysis Summary

The biomechanical analysis serves as proof of principle that an assistive device can be designed to reduce some of the demand currently placed on the neck muscular due to the NVG. To reiterate, the model was developed to: (a) examine the current system, (b) determine the magnitude of the restorative force needed in a device to counterbalance the NVG with no CW and (c) to examine a proposed device under two conditions: no batteries or with batteries on the helmet. For all analyses, the head + helmet (daytime) condition was considered the gold standard. With NVG, CW and battery pack attached to the helmet, the moments were relatively balanced in the neutral position. However, when the head was flexed to 40°, the moments climbed quickly to ~ 4 Nm for both the batteries alone and batteries plus CW. This occurred because the effect of gravity increases with increased flexion angle. At their highest, external compressive forces were 20 N higher than daytime conditions and shear forces are ~15 N higher when the CW was used. Adding weight as a counterbalancing approach is not a good strategy as it works best in the neutral position only. Therefore, the CW approach should be abandoned. A new approach that includes a constant tension spring rather than a CW is a good idea because: 1) it lowers the overall mass and moment of inertia of the head-helmet system; and, 2) it provides a restoring force that is not gravity dependent.

3 Verification and Refinement Strategy

The research team employed two methods dually purposed to verify the fundamental design concept and to provide feedback to inform refinement. Method one was a laboratory-based study where indicators of performance, perceived exertion and muscle activity were recorded while non-aircrew volunteers completed simulated aircrew tasks using different helmet configurations. Method two was a field-based study where subject matter experts were asked to try-out the device (on the ground) and provide feedback about its potential impact (positive and negative) if applied in operation.

3.1 Lab-Based Verification Methodology

3.1.1 Participants:

Twelve participants were recruited from the general student population. Seven males (age = 23 ± 5 years; mass = 82.6 ± 19.8 kg; height = 182.3 ± 4.9 cm) and five female (age = 21.0 ± 1.7 years; mass = 70.6 ± 7.7 kg; height = 166.6 ± 12.1 cm) participated. All participants provided informed consent prior to participation. This study was approved by the University's Ethics Review Board.

3.1.2 Research Design:

A block-randomized within participant design was used to test for differences in outcome measures as a function of the helmet systems configurations. Each test block was configured to balance the order in which conditions were presented (after completing the protocol in the traditional condition) and the order of positions used when completing the tasks (Figure 27). In each condition and position, the vigilance task was completed first, followed by the endurance condition. Participants were required to visit the lab on three separate occasions, separated by at least 24 hours, where they completed the protocol in only one of the test conditions on each occasion.

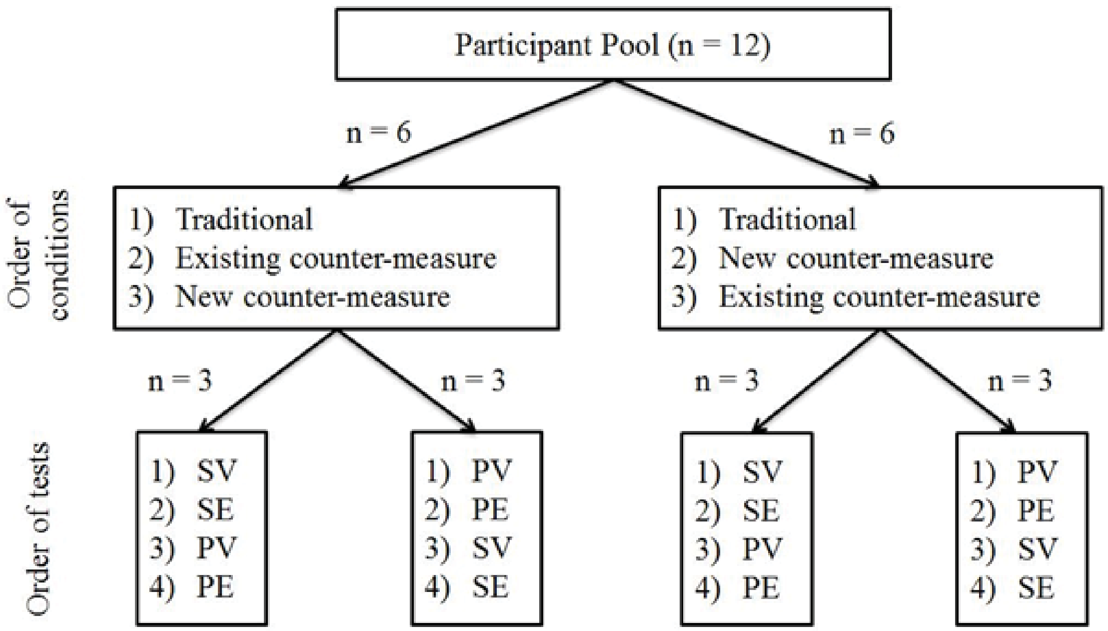

Figure 27 – Experimental design diagram to indicate block-randomized groupings.
SV – Seated Vigilance; SE – Seated Endurance; PV – Prone Vigilance; PE – Prone Endurance

3.1.3 Experimental Conditions and Test Positions:

Three different helmet conditions were evaluated: traditional, existing counter-measure, and new counter-measure. The traditional configuration included the helmet with attached simulated NVGs. The existing counter-measure configuration included the helmet with attached simulated NVGs and a CW. The new counter-measure configuration included the helmet with attached simulated NVGs and the prototype device.

Participants were evaluated in two test positions, seated and prone, completed in the prescribed blocked-randomized order for each visit. In the seated position, participants were asked to sit upright in an armless chair. The seated position was intended to simulate the pilot in the cockpit. In the prone position, participants were asked to lie on their stomach with the head, neck, shoulders, and torso (above xiphoid process) extending off of the edge of a stretcher. Participants were allowed to brace themselves with their hands at the end of the stretcher. This position was intended to simulate one of the extreme postures adopted by the flight engineer as they survey the ground during landing. A 15-minute washout period was provided between positions.

3.1.4 Protocol:

Participants performed three repetitions of maximum voluntary contractions (MVCs) in four different postures to determine maximum muscle activity of the neck muscles. Participants were given one minute of rest between each set of contractions. Uni-lateral shoulder shrugs were performed against manual resistance while in a seated position to measure maximum muscle activity for the right upper trapezius (RUT) and left upper trapezius (LUT) as per (Greig, 2005). To measure the maximum muscle activity of the cervical paraspinal muscles (CPS) participants

were asked to extend their head and neck against manual resistance (Greig, 2005). Maximum activity in the sternocleidomastoid muscle (SCM) were measured similarly, expect participants were asked to flex their head and neck forwards against manual resistance (Greig, 2005). Each exertion lasted five seconds. Participants were instructed to ramp up to their maximum during the first two seconds, and maintain their maximum for three seconds. For CPS and SCM, handheld force gauge was used to measure the force output generated by the participants in neck flexion and extension.

The seated vigilance (SV) and prone vigilance (PV) tests required participants to rapidly shift their gaze between the center target (n0) eight different target locations (n1...n8) (Figure 28). Participant began by fixing their gaze on the center target (n0) then moved their gaze back and forth between each numbered target and the center location in succession forwards and backwards (i.e. n1-0, n2-0 … n8-0). Gaze directions were monitored using a laser pointer attached to the helmet between the lenses of the simulated NVGs. During the SV and PV tasks, participants were required to aim the laser pointer directly into the center of each target, before proceeding to the next target in the sequence. Each square target was 3cm in diameter and the participant was positioned at a distance of 1m from the centre target. During the SV task the center of Target 0 was adjusted to the seated eye level of each participant. During the PV task, the center of Target 0 was positioned directly below the participants' eye line as they lied prone with their head and neck in a neutral position parallel to the floor. The distances from the center point to each of the outside targets were determined such that they required participants to move through approximately 30 degrees of neck rotation (yaw), and/or tilt (pitch) to focus on each target. Within each position, participants completed three repetitions of the vigilance task with one minute of rest in between each repeat. Participants hit each target in the specified order before advancing to the next target. Failure to do so resulted in a stopped and repeated trial. The time to complete each trial was recorded and the number of errors causing a repeated trial was documented.

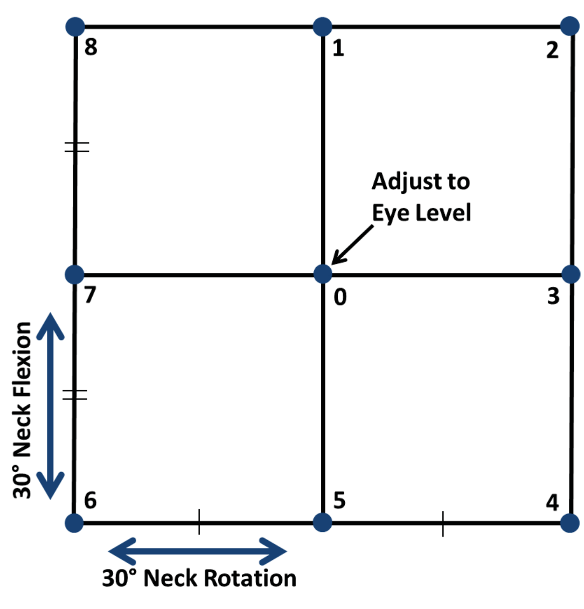

Figure 28 – A schematic illustration of the target mapped used for the vigilance task.

The seated endurance (SE) test required participants to complete an active scanning task as well as maintain a static posture periodically for a total duration of 10 minutes. During the SE task, participants were seated at a distance of 1m from the targets (3cm diameter). The static posture was held with a gaze focused on Target 5 for 10 seconds. The scanning component required participants to start on Target 0 and repeatedly alternate between Target 4 and Target 6, returning to Target 0 in between. This was done at a metronomic pace of 45 beats per minute for a length of 49 seconds. Participants began and ended the SE test by holding the static posture for 10 seconds. They alternated between completing the static posture and the scanning component until the 10 minute test was complete.

The prone endurance (PE) test required participants to maintain a static posture until volitional fatigue, or to a maximum duration of 10 minutes. During the PE task, prone participants were positioned as noted for the PV test; however, this time they were asked to maintain the position of the laser pointer within the 3 cm square target of the floor until volitional fatigue. Endurance time was calculated from test on-set, until the time when the participant could no longer maintain the laser's position within the square target.

3.1.5 Outcome Measures:

Three classes of outcome measures were recorded including: performance, perceived effort, and muscular demand. Performance in each test activity (SV, PV, SE, PE) was measured by recording the time to completion / volitional fatigue. At the conclusion of each activity, participants were also prompted to provide subjective feedback regarding their perceived effort to complete the activity. Perceived effort was gathered using a Borg CR-10 scale (Borg, 1990). Muscular demand was measured using electromyography (EMG). EMG was recorded from three muscles bilaterally, including: sternocleidomastoid, the cervical paraspinal muscles, and upper trapezius with surface electrode placement according to Ferrario et al., (2006), Burnett et al., (2009), and Zipp (1982) respectively. EMG was normalized to the muscle activity obtained during respective maximal voluntary contraction in order to compare the relative EMG activity between helmet configurations.

Twenty-four hours following the completion of all test conditions, participants were e-mailed to solicit feedback about their preferred helmet system configuration. Participants were asked to rank order each helmet condition from 1 – most preferred, to 3- least preferred in the seated and prone postures separately and were also provided an opportunity to comment/justify their ordered list.

3.1.6 Statistical Analysis:

One-way repeated measures analysis of variance (ANOVA) was applied to detect for differences in outcome measures between the three different helmet system configurations. An alpha value of 0.05 was used to determine significant difference in the ANOVA model. Greenhouse-Giesser corrections were applied when the data did not meet the sphericity assumption, according to Mauchly's test of sphericity. Pairwise comparisons were applied post hoc when significant main effects were detected.

3.2 Field-Based Verification

To verify that the concept had merit during inflight operation, the team travelled to CFB Borden to meet with CF Griffon aircrew from the 400 Squadron. The purpose of this qualitative research component was to gather specific insight and feedback about the design concepts. This feedback was essential for three reasons. First, it provided the research team with insights about which design concepts, or elements with each concept were preferred by aircrew. Second, it provided a forum to discuss and identify possible concerns that may affect flight safety and/or operational capability. Lastly it provided an opportunity to loosely contrast the design concept(s) against the current counter-weight solution.

3.2.1 Subject Matter Experts

Nine current 400 Squadron members were asked to provide insight about the design concepts. Three were affiliated with the Aviation Life-Support Equipment (ALSE) team and provided specific insight regarding attachment points and airworthiness concerns with respect to on-body and on-helmet mounting approaches. Two were current flight engineers and provided specific insight based on their role in the cabin of the aircraft. Four were active duty pilots and provided specific insight based on their role in the cock-pit of the aircraft.

3.2.2 Interview Guide

A semi-structured interview approach was used to gather feedback from the CF personnel. Considering the nature of this phase of the research, a brief list of introducing questions ("can you tell me about …") were prepared to generate discussion, and then the team used follow-up and probing questions ad hoc, to facilitate CF personnel in elaborating on specific topics. A summary of introducing questions is provided in Table 3. ALSE personnel were interviewed together as a group, where aircrew were interviewed individually to ensure that each had an opportunity to share their own thoughts and perceptions without being impacted by the thoughts and ideas of their colleagues. During each interview, the design concepts were introduced and explained to each subject matter expert. They were then asked to try on the different concepts, and simulate the range of typical activities that they perform while in the CF-146 helicopter.

Table 3 – Introduction questions used to guide semi-structured interviews with CF personnel

ALSE Personnel	Flight Engineers	Pilots
Can you describe all of the types of equipment that aircrew might wear (seasonal, or geographical considerations)?	[After trying on the device] What to you like and dislike about the device?	[After trying on the device] What to you like and dislike about the device?
What is the typical maintenance cycle for life preserver safety vest (LPSV) and helmet?	Do you normally wear the counter-weight [existing solution to mitigate neck pain]? How does this device compare to wearing the counter-weight?	Do you normally wear the counter-weight [existing solution to mitigate neck pain]? How does this device compare to wearing the counter-weight?
If you want to make a modification to any equipment, what protocol / process is followed?	Considering the different concepts, which variations do you prefer most?	Considering the different concepts, which variations do you prefer most?
If you were going to attach this [the device] to the helmet and the LPSV, how would you fasten it?	Can you foresee any problems when wearing this device during operation? How might the device limit your capability in any way?	Can you foresee any problems when wearing this device during operation? How might the device limit your capability in any way?
	Would you wear the device today if it was approved?	Would you wear the device today if it was approved?

4 Verification Results and Discussion

4.4 Lab-Based Verification Results

4.4.1 Seated Vigilance Task

The helmet configuration had an effect on all key outcome measures: performance, perceived exertion, and muscular demand (Figure 29). Performance was significantly effected ($F(2,20) = 6.802$, $p = 0.005$, $\eta p^2 = 0.382$), where post-hoc pairwise comparisons revealed that participants were able to complete the task 3.6 ± 1.1 sec faster when wearing the new counter-measure device, relative to the baseline helmet and NVG condition ($p = 0.021$)

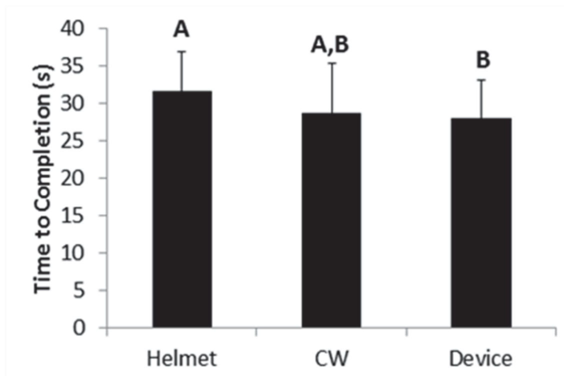

Figure 29 –Time to complete the seated vigilance task for each helmet system configuration. Bars represented with the same letters are not significantly different from one another (i.e. A is significantly different from B, but A, B is not significantly different from either A or B).

Rate of perceived exertion (RPE) was also effected by the helmet configuration ($F(2,20) = 6.440$, $p = 0.006$, $\eta p^2 = 0.369$) (Figure 30). Participants perceived the task to require less exertion (1.03 ± 0.3 units on a 10-point scale) when wearing the new counter-measure device relative to the helmet condition ($p = 0.010$).

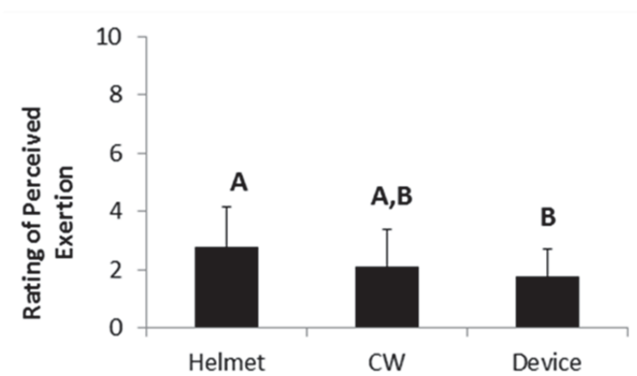

Figure 30 – RPE when completing the seated vigilance task for each helmet system configuration. Bars represented with the same letters are not significantly different from one another.

When considering the neck muscle effort, a modest benefit was realized when wearing the new counter-measure device (Figure 31). The cumulative right cervical paraspinal muscle (CPS) muscular effort was reduced wearing the new counter-measure device ($F(2,20) = 6.499$, $p = 0.006$, $\eta p^2 = 0.371$).

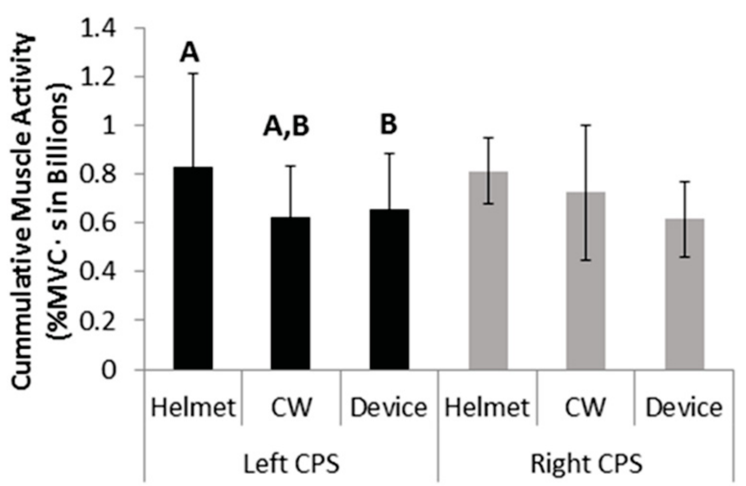

Figure 31 – Integrated (cumulative) normalized EMG activity from the right and left cervical paraspinal muscles when completing the seated vigilance task for each helmet system configuration. Bars represented with the same letters are not significantly different from one another.

4.4.2 Seated Endurance Task

All participants were able to endure the maximum exposure time of ten minutes in this task in each helmet configuration. Participants did not perceive any differences in the exertion required to complete as a function of the helmet system configuration. Muscle activity has not yet been analyzed for this activity.

4.4.3 Prone Vigilance Task

Performance and muscle activity were affected by helmet configuration during the prone vigilance task (Figure 32). Similar to results during the seated vigilance task performance was significantly effected ($F(2,20) = 4.588$, $p = 0.023$, $\eta p^2 = 0.315$), where post-hoc pairwise comparisons revealed that participants were able to complete the task 3.3 ± 1.0 sec faster when wearing the new counter-measure device, relative to the baseline helmet and NVG condition ($p = 0.021$).

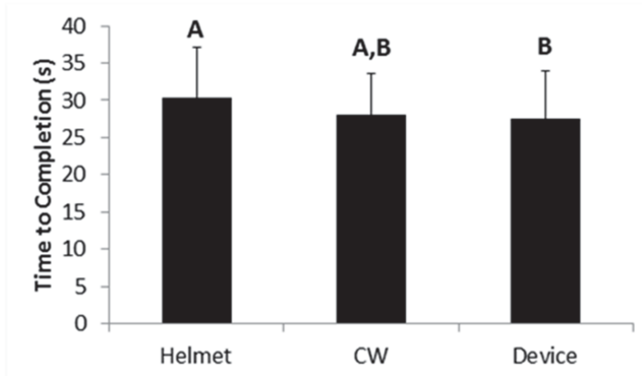

Figure 32 – Time to complete the prone vigilance task for each helmet system configuration. Bars represented with the same letters are not significantly different from one another.

Positive benefits of the new counter-measure device were demonstrated in the right cervical paraspinal muscles when completing the prone vigilance tasks (Figures 33 & 34). A significant decrease in mean muscle activity ($F(2,20) = 9.173$, $p = 0.001$, $\eta p^2 = 0.478$), and cumulative muscular effort ($F(2,20) = 8.054$, $p = 0.003$, $\eta p^2 = 0.446$) was realized when wearing the new counter-measure

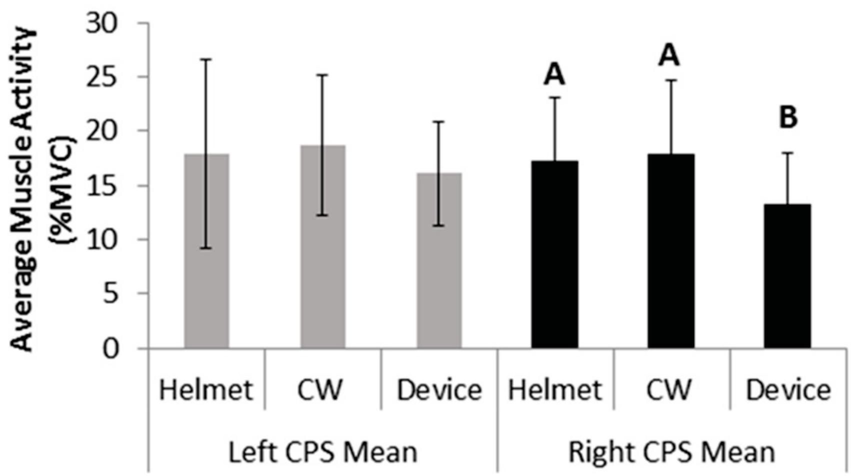

Figure 33 – Mean normalized EMG activity from the right and left cervical paraspinal muscles when completing the prone vigilance task for each helmet system configuration. Bars represented with the same letters are not significantly different from one another.

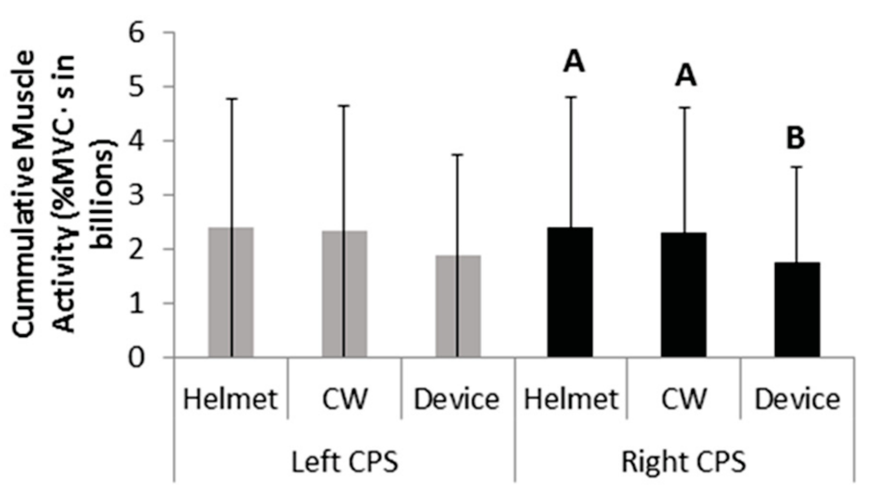

Figure 34 – Integrated (cumulative) normalized EMG activity from the right and left cervical paraspinal muscles when completing the prone vigilance task for each helmet system configuration. Bars represented with the same letters are not significantly different from one another.

4.4.4 Prone Endurance Task

Performance and RPE were affected by the helmet configuration when performing the prone endurance tasks (Figure 35). Participants were not able to endure as long when wearing the counter weight, relative to the other two conditions ($F(2,20) = 7.348$, $p = 0.004$, $\eta p^2 = 0.400$). On average, participants were able to hold the prone posture for 2.7 ± 0.8 minutes longer when using the device versus the counter weight ($p = 0.022$).

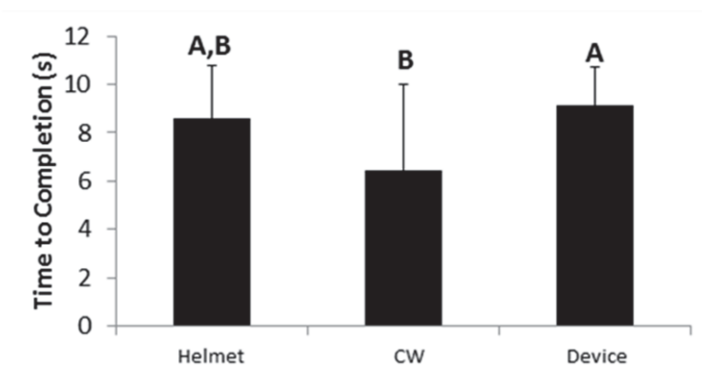

Figure 35 – Endurance time during the prone vigilance task in each helmet system configuration. Bars represented with the same letters are not significantly different from one another.

Participants perceived the counter weight condition to require more physical exertion than the other conditions ($F(2,20) = 17.022$, $p < 0.001$, $\eta p^2 = 0.607$) (Figure 36). Participants perceived the task to require less exertion (1.6 ± 0.3 units on a 10-point scale) when wearing the new counter-measure device relative to the counter weight condition ($p < 0.001$).

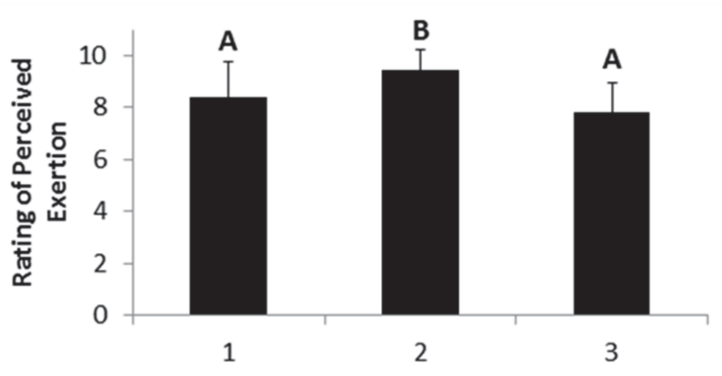

Figure 36 – RPE when completing the prone endurance task for each helmet system configuration. Bars represented with the same letters are not significantly different from one another.

4.5 Field-Based Verification Results

The field-based verifications yielded essential insights. On one hand, the feedback from CF aircrew was very positive regarding the fundamental concept of using a constant force spring to counter-balance the weight of the helmet. However, feedback also revealed that the current concept needs further refinement to better facilitate full range of motion. For example the current iteration of the track system to provide more rotational freedom imposed an unintended effect where aircrew required more effort to return back to the center position. A summary of the specific feedback is presented in Table 4.

Table 4 – A summary of the general comments and feedback provided by members of the 400 Tactical Helicopter Squadron stationed at CFB Borden

ALSE Personnel	Flight Engineers	Pilots
Although the ALSE is standard in Canada, in theatre, aircrew may wear other equipment, such as the “eagle” or “mustang” vests.	The box on the back is uncomfortable [when wearing Design 2b]. Adjustable balancing moment is good idea. One FE preferred the fixed helmet mount (Design 2a/2b) while the other preferred the track system assuming it could be refined (Design 1 / 3)	Difficult to look up when wearing the device. The box on the back was uncomfortable. Sound in the track system was annoying. Fixed attachment design (2a/b) helped to maintain fixed head positions.
Most ALSE equipment has a 180 inspection cycle.	One FE normally wore the CW and one did not. Both agreed that they would wear the device and that it was better than the CW	Three of four pilots wore the CW. All agreed that the device was much better because:

	because it removed mass from the helmet. Further, one commented that it "felt awesome" after wearing it while simulations job tasks in the helicopter.	– Less mass on head – Constant balancing force – CW is sloppy and requires more head/neck control
All modifications need to be passed through the Director General Aerospace Equipment Program Management (DGAEPM) team in Ottawa including the Life Cycle Material Manager (LCMM) for vests and helmets.	FEs were not concerned about trying to use the device (donning/doffing/adjusting) while wearing gloves or in operation. However concerns included: binding of the spring due to dust (i.e. in Afghanistan) and the ability to quick release during egress; particularly under water in the event that it snagged on the fall arrest harness. There were no concerns about the system negatively limiting capability.	Mixed responses: Some preferred the fixed mount, while other preferred the track system (with refinement). All agreed that the balancing concept had a lot of merit, but freedom of mobility needed to be maintained. Pilots enjoyed the quick release option rather than the snap in option, and one pilot noted that if the spring was very low mass, it could be place on the helmet rather than on the back to improve comfort.
Any track system should likely use a fixed mounting on the helmet; however, a Velcro based attachment on both the helmet and vest would likely be the easiest to implement and maintain.	Yes, both agreed that they would wear the device if minor refinements were made to address comfort (the size of the lower attachment point) and the freedom of motion in the track system.	Yes, ALL pilots agreed that they would wear the device pending minor refinements. One pilot asked "can I take it flying tonight". The key concerns to be addressed through refinement included, an improved track system to accommodate a full range of motion, and improved comfort by shrinking or removing the box at the lower attachment point.

4.6 Discussion of Verification Results

The aim of this project was to develop, verify and refine an engineering-based solution to address aircrew neck strain. In doing so, a list of general target specifications were considered (more completely defined in Annex A), as per the needs of CF aircrew. The proceeding discussion will verify our results against that list.

4.6.1 Reduce the mass on the head

Reducing the mass on the head has a clear benefit. The ***new counter-measure device results in 10% less head-borne mass*** by allowing users to replace the existing counter weight (0.917 kg – Table 2) with the devices' attachment weighing less than 0.153 kg (as per Design Specification – Annex A). Indeed all flight crew interviewed unanimously agreed that reducing the head-borne mass was of critical importance (Table 4).

Although only a minor focus in the biomechanical analysis (Section 2), the batteries attached to the head also add 0.34 kg (0.75 lb) weight to the helmet. If a new counter-measure device were implemented, the aircrew should consider other locations for the battery pack such as on the shoulder or in a pocket of the vest.

The current added mass of the existing counter-weight approach has a number of limitations that may actually be causing more harm than good. For example, the prone testing task performed during the lab verification study revealed that the use of the counter weight actually decreased performance relative to the other two conditions (Figure 35). Further, many aircrew noted that while the counter-weight was okay when in an upright seated posture; the added weight and inertia it generates actually causes the whole helmet system to translate relative to the head (Table 4). This is an operational risk as the helmet could slip down on the forehead, momentarily clouding a pilot's ability to see.

In light of the results from this study, it is clear that the new counter-measure device reduces the mass on the head. Further, aircrew want solutions that reduce the mass on their head, making the new counter-measure and ideal option.

4.6.2 Lower the inertia of the head-helmet system

Coincident with lowering the helmet mass, ***the new counter-measure also lowers the inertia of the head helmet system***. Reduced inertia will reduce the muscular effort required from the small muscles of the neck when starting or stopping neck movements. Indeed, aircrew commented that the new counter-measure device allowed them to move more naturally as a result of the consistent balancing force. By contrast aircrew noted that the existing counter weight option is sloppy and requires a lot more head and neck control [in part, to overcome the higher inertia] (Table 4).

In light of the reduced mass and the feedback from aircrew, it is clear that the new counter-measure device lowers the inertia of the head-helmet system. This reduction in inertia was valued by aircrew, as they felt that it reduced the effort needed to control their head position when initiating or stopping head movements (i.e. looking down to the control panel when in the cockpit).

4.6.3 Reduce neck muscular demand (to day flight levels at a minimum)

The new counter-measure device was intentionally designed to provide a balancing moment to the back of the helmet that would reduce the effort required by the neck extensor muscles. Based on the results of the modeling analysis captured in Figure 12, by applying a constant restorative force of approximately 8 N, the required neck extensor moment can be restored to match the moment demands experienced during day flight.

Additionally, EMG data from the lab verification study also support this finding. Although EMG data, a non-stationary, relatively noisy electrical signal is highly variable; results indicted several modest benefits, especially for the cervical paraspinal muscles. In all conditions investigated, the EMG required to complete tasks while wearing the new counter-measure device was either the same as, or less than the activity required to complete the same task when wearing just the helmet and NVGs, or helmet NVGs and counter weight (Figures 31, 33, and 34).

Based on the results of this work, we conclude that ***the new counter-measure devices reduces the neck muscle demand to that equal to or even less than the demand experienced during typical day flights***.

4.6.4 Reduce overall neck compression and neck moments

It is anticipated that the new counter-measure device will reduce the overall neck compression experienced by the cervical vertebrae in comparison to the current approach. Bone-on-bone compression emerges as a results of two key factors: external reaction forces (i.e. weight of the head helmet system), and internal forces (muscles). Based on our biomechanical modeling analysis, the new counter-measure device reduces the reaction compression experienced by the spine to 72 N, which is only 4N less than the current counter weight approach. However, it does increase the neck compression (relative to the helmet and NVG condition) by approximately 5 N which is likely negligible for most aircrew members (See Figure 21 and 22). These calculations consider only external reaction forces and do not address factors related to vibration, muscular co-contraction, or cumulative loading over the duration of a mission. African women and Nepalese porters during head carries average loads of 263 N (59 lbs) (Lloyd et al., 2010) and 441 N (99 lbs) (Bastien et al, 2005) respectively. However, they cannot sustain these large loads during any neck flexion or rotation and the vibration frequencies are dramatically different.

Neck moments are also affected by the new counter-measure device. As shown in the biomechanical model Section 2, Figure 8, the current system of CW and batteries system causes ~4.3 N.m at 40° of neck flexion. By applying the 8 N counter force at a distance of 13 mm from the atlanto-occipital joint, the neck moment is reduced at 40° of neck flexion to 3.5 Nm (20%) as shown in Section 2, Figure 15. The combined effect of reductions in neck compression and neck moments should result in reduced muscular effort as well. Since many of the atlanto-occipital joint muscles are deep, aircrew perceptions may be the easiest method of judging muscular effort.

At this stage we are not able to estimate the effect of internal muscles forces on compression. All muscles pull when they are active, such that they also compress the materials in between. Considering that the new counter-measure device reduces the amount of force that would need to be generated by the muscles to balance the head; we believe that this will in turn reduce the internal muscles forces acting to compress the spine. While it is difficult to estimate the reduction without access to higher fidelity biomechanical models, it is believed that the reduction in muscle-driven compression would be greater than the 5 N increase in reaction compression noted above. Therefore it is anticipated that the net results will be reduced compression on the neck.

Based on the results of this study ***the new counter-measure device is likely to results in less overall neck compression***.

4.6.5 Accommodate a full range of motion

Pilots and flight engineers must be able to move through a wide range of neck motions to complete their operational duties. For example, when using NVGs pilots spend nearly 80% of their flight time in forward flexed posture between 10-30°; and, up to 60% of their time in axially twisted postures ranging from 10-40° (Forde et al., 2011). Therefore it is critical that any new counter-measure does not impose restrictions that would jeopardize aircrew's ability to move through this range of motion.

As indicated in the biomechanical analysis (subs-section 2.6.3) the application of a constant force to a fixed point on the back of the helmet will require a modest increase in the moment required to twist the head. Feedback from aircrew (Table 4) corroborated that point, noting that the fixed attachment point was great when moving in the flexion/extension plane; however, it required a little more effort to move in other planes and that would "take some getting used to".

Participants in the lab verification also commented about the different feelings experienced when rotating outside of the flexion/extension plane. Both the seated and prone vigilance tasks challenged participants to do just that when transitioning their gaze to the 2, 3, 4 and 6, 7, 8 positions on the target map (Figure 25). However, despite their comments they perceived (RPE) the task to require less neck effort when wearing the new counter-measure than when wearing the helmet and NVGs (Figures 30 and 32). Coincident with this discrepancy between the comments and the RPE data, some aircrew also noted that they preferred this added restorative force when moving outside of the flexion/extension plane (Table 4).

Based on the outcomes of this research, ***we concluded that the new counter-measures needs to be further refined to better accommodate non-flexion/extension plane motions***. However, given the contrasting results on this issue, ***in the near-term the current device is likely more than acceptable without refinement, where aircrew may need a brief accommodation period to get used to the new line of action of force relative to the current conditions***.

4.6.6 Allow for individual user adjustability (adjustable off-load)

Ergonomics is rooted in human centred design, where individual adjustability and customization is essential. Through the generate concepts phase of the process (Section 1.3.3) two methods of adjustability were conceived. One allowed the user to adjust the moment arm by which the restorative forces acted, while the other allowed users to increase or decrease the force directly. Our preliminary work (Annex C) supported the need for adjustability where participants preferred a lighter balancing moment when sitting upright; but more balancing moment when lying prone during a simulation the flight engineers under aircraft surveillance task.

Aircrew also enjoyed the ability to personalize the balancing moment to their liking. Some aircrew preferred less balancing moment, where others preferred more, even when simulating the same activities in the aircraft (Table 4). This is likely due to small differences in head shapes, mass distributions and helmet fit, in addition to differences in perceptions. However, the field-based verification revealed that aircrew were generally more supportive of adjusting by increasing the force, rather than by increasing the moment arm.

Adjustability is also a core element in developing a common solution platform that might be used in a variety of applications within and apart from the helicopter community. For example, land forces using monocle night-vision systems could potentially use the same mechanism, lowering development, testing and manufacturing costs.

The results of this work indicate that ***adjustment is an important feature that aircrew value***. After probing for their preferred method of adjustment, most preferred to be able to wind a dial to increase or decrease force, rather than adjusting the moment arm directly. This refinement will be addressed in the next design iteration.

4.6.7 Be easy to engage and disengage

The ability to engage and disengage the device seamlessly is very important in such a dynamic work environment. We evaluated this specification by considering the guidance and insights of aircrew. Firstly, aircrew noted that there is plenty of time prior to a mission (training or in theatre) to allow the entire new counter-measure device to be attached the LPSV and helmet. This is important as it is likely that aircrew will need to attach the device (like they attach the current counter weight) to their equipment before flying. However, once the device is attached to the equipment, it was important to ensure that the cable could be easily engaged and disengaged from the back of the helmet using one hand.

Aircrew were observed engaging and disengaging the device during the field-based verification. No concerns emerged when requiring aircrew to reach behind their neck to grab the cable fixture and to extend it up to place it on the back of the helmet. When offered two different options to secure the cable to the helmet; a slide in and a snap in option, aircrew preferred the slide in option (Table 4). Therefore the next design iteration will ensure that the cable is engaged and disengaged using a slide in-based fixation.

The results of this work indicate that ***the new counter-measure is easy to engage and disengage***. Aircrew agreed that the ability to engage and disengage the balancing cable using a slide in-based mechanism would be ideal.

4.6.8 Low intrusion on operational environment

Any impingement on the operation capability of aircrew must be avoided. As such one of the major concerns through-out the design process has been: how might this device affect aircrew's capability during operation, particularly for the flight engineer when performing dynamic activities throughout the cabin of the helicopter? Indeed, aircrew did mention some possible concerns in extreme situations (i.e. dust affecting the counter-measures performance) (Table 4). However, when asked "would you wear the device today if it was approved?" all aircrew agreed that they would wear the device. When probed further: "would you be concerned about how the device might limit or affect your operational capability in any way?" again, aircrew were unanimous in noting that the device would not pose any imposition on their abilities. In fact, one aircrew member noted, "in terms of its size and location, I hardly even know it's there."

As the new counter-measure design is refined further towards a production ready device, the design will need to ensure that all moving parts are adequately protected such that dust or other environmental factors will not be able to penetrate and affect the performance of the device.

Further, based on the opinions of current-service aircrew, the device is not expected to adversely affect operational capability.

The results of this work indicate that ***the new counter-measure device does not intrude or interact with the operational capabilities of the aircrew or environment of the aircraft***. The next steps to further evaluate this specification requires that aircrew be able to wear the new counter-measure while performing simulated or real in-flight operations within the Land Aviation Test and Evaluation Flight framework.

4.6.9 Robust

The rigors of flying a military aircraft demand that equipment and ergonomic aids are robust. While the current prototypes have been developed using plastic and parts created using 3D printing technology, through conversation with potential production/manufacturing partners it is clear that this device can be built to withstand the demands of helicopter flying.

Consistent with other ALSE equipment, the new counter-measure will have an inspection cycle of approximately 180 days (Table 4). However, to minimize inspection requirements, the new counter-measure will be produced such that ASLE technicians will only need to visually inspect the casing, cable, and check the cable tension. In the event that the cable tension has been compromised it may be feasible to easy open the casing and swap out the compromised spring with a new spring; or conversely, depending on product pricing, it may be more feasible to simply replace the device. Considering the aircrew spend relatively few hours flying with NVGs relative to normal day-time flying, it is expected that the new counter-measure device will be more than capable to handle the typical volume of NVG flying experienced by aircrew.

The results of this work indicate that ***the new counter-measure device will be robust and easy to inspect on the normal 180 ALSE equipment inspection cycle***. The device will be able to withstand the environmental conditions experienced by aircrew, whether flying in extreme arctic or dessert climates.

4.6.10 Cost effective to manufacture

At this stage in the process we can only anticipate that the device will be cost effective to manufacture. In its current design, very few parts are required to build each device, keeping material and assembly costs low. However, as we move forward to establish a production ready design in partnership with a producer/manufacturer, we will be better positioned to comment on this specification.

4.6.11 Next Steps

The results of this work indicate that the new counter-measure device is an improvement from the existing counter weight approach, and is welcomed by aircrew. Through this process the design team has also received insightful feedback from aircrew and have been informed by lab verification data such that we can move forward to establish a production ready design. However, the next critical step transitions our team away from R&D towards developing the business case. With minor refinements, the new counter-measure shows promise as a near term solution to address aircrew neck strain. But, before the CF community can trial the new counter-

measure within the Land Aviation Test and Evaluation Flight framework, production-level products need to be developed. In the short term, two options persist to further develop this technology. Option one continues to rely on funding from government/military sources. In this model, the research team would leverage funding from the government to develop a small number of production-level devices that could be used to support field evaluation within the Land Aviation Test and Evaluation Flight framework. With a modest financial investment, we could quickly learn just how big the benefits of this new counter-measure might be with respect to reducing aircrew neck pain. In this model, government monies would directly support the engineering required to refine the device, procure the parts, and assemble the devices.

Options two invites more collaboration with the private sector. Considering the world-wide scope of NVG-induced neck pain among helicopter aircrew, and the strong evidence that this counter-measure will help to address NVG induces neck strain; it is foreseeable that a private company would champion the continued development. In this model, with the support of DRDC, the research team would move to conduct a business case that could be used to solicit investment from the private sector. The business case would need to demonstrate the need for the product (which is clear considering the most recent data from DRDC's neck strain survey), the size of the market (how many devices are likely to be purchased by Canada, USA, other NATO air, land and sea forces, etc.), and the anticipated ongoing development costs. However, in this model the private enterprise would then assume the financial costs (and risks) associated with developing production-level devices for use in Land Aviation Test and Evaluation Flight framework-based testing.

The next step in this process requires that the current new counter-measure design be refined into a production-ready device. This refined device will then need to be evaluated within the Land Aviation Test and Evaluation Flight framework to further validate the positive benefits outlined in this report, and to ensure that aircrew operational capability and safety are not compromised. Aircrew agree that this near-term solution provides an "awesome" option to help mitigate aircrew neck strain. We look forward to progressing forward to get this device in the hands of aircrew so we can indeed begin to reduce the prevalence of neck strain among helicopter pilots.

References

1. Adam J. Results of NVG-induced neck strain questionnaire study in CH-146 Griffon aircrew. Defence R&D Canada Toronto ON. DRDC Toronto 2004; TR 2004-153.

2. Andrews, D., Callaghan, J., 2003. Determining the minimum sampling rate needed to accurately quantify cumulative spine loading from digitized video. Applied Ergonomics 34 (6), 589-596.

3. Ang, B. (2007) Neck pain in air force pilots: on risk factors, neck motor function and an exercise intervention [Dissertation]. Karolinska Institutet, Stockholm, Sweden; 2007.

4. Ang B, Linder J, Harms-Ringdahl K. Neck strength and myoelectric fatigue in fighter and helicopter pilots with a history of neck pain. Aviat Space Environ Med 2005; 76:375-80.

5. Ang B & Harms-Ringdahl, K. Neck pain and related disability in helicopter pilots: a survey of prevalence and risk factors. Aviat Space Environ Med 2006; 77:713-9.

6. Bastien GJ, Schepens P, Willems PA, Heglund NC (2005b). Energetics of load carrying in Nepalese porters. Science 308:1755-62.

7. Burnett, A., O'Sullivan, P., Caneiro, J.P., Krug, R., Bochman, F., Helgestad, G.W. (2009) An examination of the flexion relaxation phenomenon is the cervical spine in lumbo-pelvic sitting. Journal of Electromyography and Kinesiology. 19(4):229-236.

8. Butler BP. Helmeted head and neck dynamics under whole-body vibration [Dissertation]. University of Michigan, Ann Arbor, United States of America; 1992.

9. Callaghan, J.P. (2006) Cumulative spine loading. InW.S. Marras,W. Karwowski (eds). The Occupational Ergonomics Handbook second ed.: Fundamentals and Assessment Tools for Occupational Ergonomics, CRC Press, Chapter 13.

10. Chen Y, Wickramasinghe V, Zimcik D. Adaptive mount approaches for helicopter seat vibration control. Proceedings of ICAST 2007.

11. Chen Y, Wickramasinghe V, Zimcik DG. (2008) Development of adaptive helicopter seat systems for aircrew vibration reduction. J Vib Control 2009; 15: 1809-25.

12. Craig J, Task, L, Filipovich D. Development and evaluation of the panoramic night vision goggle. Air Force Research Laboratory Wright-Patterson AFB, OH. 1997; ASC97-0507.

13. Greig, A. (2005) Cervical erector spinae and upper trapezius muscle activity in children using different information techniques. Physiotherapy. 91:119-126.

14. Ferrario, V.F., Tartaglia, G.M., Galletta, A., Grassi, G.P., Sforza, C. (2006) The influence of occlusion on jaw and neck muscle activity: A surface EMG study in healthy young adults. Journal of Oral Rehabilitation. 33(5):341-348.

13. Fischer SL, Stevenson JM, Reid SA, Chow J, Bryant JT. “Near-term ideas to address helmet systems-induced neck pain” Interim Report for Task 31 Contract # W7714-12-5624/001/SV (DRDC Toronto CR 2013-039), 2013.

14. Forde KA, Albert WJ, Harrison MF, Neary JP, Croll J, Callaghan JP. Neck loads and posture exposure of helicopter pilots during simulated day and night flights. Int J Ind Erg 2011; 41: 128-35.

15. Fraser S, Alem N, Chancey VC. Helicopter flight performance with head-supported mass. Proceedings of American Helicopter Society 62nd Annual Forum. 2006. \

16. Gallagher HL, Caldwell EE, Albery C, Pellettiere J. Neck muscle fatigue resulting from prolonged wearing of weighted helmets. Aviat Space Environ Med 2007; 78:233.

17. Geiselman EE, Craig JL. Panoramic night vision goggle update. Air Force Research Laboratory Report ASC 99-2379, 1999; 1-6.

18. Harms-Ringdahl K, Ekholm H, Schuldt K, Linder J, Ericson MO. Assessment of jet pilots’ upper trapezius load calibrated to maximal voluntary contraction and a standardized load. J Electromyogr Kines 1996; 6: 67-72.

19. Harrison MF. The investigation of muscular factors in night vision goggle induced neck strain in Canadian Forces helicopter aircrew [Dissertation]. University of Regina, Regina, Canada; 2009.

20. Harrison MF, Neary JP, Albert WJ, Veillette DW, McKenzie NP, Croll JC. Trapezius muscle metabolism measured with NIRS in helicopter pilots flying a simulator. Aviat Space Environ Med 2007a; 78:110-116.

21. Harrison MF, Neary JP, Albert WJ, Veillette DW, McKenzie NP, Croll JC. Physiological effects of night vision goggle counterweights on neck musculature of military helicopter pilots. Mil Med 2007b; 172:864-70.

22. Harrison MF, Neary JP, Albert WJ, Veillette DW, McKenzie NP, Croll JC. Helicopter cockpit seat side and trapezius muscle metabolism with night vision goggles. Aviat Space Environ Med 2007c; 78:995-8.

23. King AI. Fundamentals of impact biomechanics: Part 1 – Biomechanics of the head, neck, and thorax. Annu. Rev. Biomed. Eng. 2000; 2:55-81.

24. Lloyd R. Parr S. Davies T. Partridge C. Cooke. A comparison of the physiological consequences of head-loading and back-loading for African and European women. European Journal of Applied Physiology. 109(4): 607-616, 2010.

25. Moroney SP, Schultz AB, Miller JAA. Analysis and measurement of neck loads. J Ortho Res 1988; 6:713-720.

26. Nordin M, Frankel VH. Basic Biomechanics of the Musculoskeletal System. 3rd Edition. Lippincott, Williams and Wilkins, Baltimore MD. 2001.

27. Salmon DM. The efficacy of exercise therapy in reducing neck pain and fatigue in CH-146 CF aircrew [Dissertation]. University of Regina, Regina, Canada. 2009.

28. Sovelius R, Oksa J, Rintala H, Huhtala H, Siitonen S. Neck muscle strain when wearing helmet and NVG during acceleration on a trampoline. Aviat Space Environ Med. 2008; 79: 112-6.

29. Thuresson M, Ang B, Linder J, Harms-Ringdalh K. Intra-rater reliability of electromyographic recordings and subjective evaluation of neck muscle fatigue among helicopter pilots. J Electromyogr Kines 2005; 15: 323-31.

30. Van den Oord MHAH, De Loose V, Sluiter JK, Frings-Dresen MHW. Neck strength, position sense, and motion in military helicopter crew with and without pain. Aviat Space Environ Med 2010a; 81: 46-51.

31. Van den Oord MHAH, De Loose V, Meeuwsen T, Sluiter JK, Frings-Dresen MHW. Neck pain in military helicopter pilots: prevalence and associated factors. Mil Med 2010b; 175: 55-60.

32. Walker LB, Harris EH, Pontius U. Mass, volume, center of mass, and mass moment of inertia of head and head and neck of human body. In: Proceedings of the Strapp Car Crash Conference, 1973; 525-538.

33. Walters PL, Cox JM, Clayborne K, Hathaway AJ. Prevalence of neck and back pain amongst aircrew at extremes of anthropometric measurements. USAARL Report No 2012-12.

34. Wickes, S., Scott, J., Greeves, J., Epidemiology of flight-related neck pain in Royal Air Force (RAF) aircrew. Aviat Space Environ Med 2005; 76, 298.

35. Yoganandan N, Pintar FA, Zhang J, Baisden JL. Physical properties of the human head: mass, center of gravity, and moment of inertia. J Biomechanics 2009; 42: 1177-1192.

36. Zipp, P. (1982) Recommendations for the standardization of lead positions in surface electromyography. European Journal of Applied Physiology. 50:41-54.

Annex A Prototype Design Specifications

System Needs

1 Balance head in neutral posture with no unbalance moment (within 5%). Estimated at 1.2 N.m for flexion-extension (~8N at 0.150 m from head COG, with user adjustability of at least +/- 10 %.)
2 Maximum additional head-borne load to be 1.5N (~153 grams) (See Table A-2 below for rationale.)
3 Reduce peak muscular effort by 10% over a typical night op flight (>1hour duration)
4 Reduce cumulative muscular effort by >≥15% over a typical night op flight (>1 hour)
5 Reduce shear loading of the cervical spine during prone postures by 15%
6 Reduce peak muscular effort during rapid horizontal motions by 15%
7 No adverse reduction in helmeted head/neck range of motion
8 No reduction in current ROM of head or torso
9 Activated and inactivated by user without external assistance
10 Engaged and disengaged with one hand (light gloves)
11 Counterbalancing compensation/adjustment controllable by one hand (light gloves)
12 When inactivate will safely self-store
13 When inactivate will not interfere with helmeted head/neck motions
14 Snagging potential minimized to same level or better of existing helmet borne equipment
15 Quick release - one hand only required, or break-away force limit
16 Concept is compatible with range of helmets
17 Training documentation provided with system
18 Device failure will not lock head motion

Operational Demands

1 No inference with ability to fully use current seating options in Griffon Helicopter
2 Compatible with all seating with supported back height no higher than current Griffon Pilot/CP seat for range of pilot bodies
3 Operational temperature range: -40ºC - + 45ºC (TBD)
4 No required physical modification to aircraft
5 No impediment of crew function (e.g. FE within aircraft, door fore/aft & below vehicle checks, gunnery).
6 Usable for over water or land operations
7 Compatible with operationally required kit (PFD, safety harness, face shields, winter clothing etc.)
8 Remain operational over full range of expected exposure to environmental factors: dirt, water, salt, dust etc.

Maintenance and Service

1 Functional system and components are field replaceable or field serviceable
2 Condition of device as ‘fit for use’ apparent to service personal and user without disassembly.
3 Materials, mounting positions and attachment mechanism (bolting/Velcro/sewing) integrate readily with existing institutional practices.

4 In compliance with all applicable identified (TBD) ‘essential’ items under governing NATO STANAGs, pertaining to:

- Flight Safety Structure Information
    - Aircrew Environmental limitations
- Flight line and Local Area Emergencies
    - Crash/fire procedures and equipment
    - Aircraft/aircrew survival equipment
- Search and Rescue
    - Theatre Procedures
    - Land and/or water survival
    - Hostile environment survival
- Environmental Testing
    - Environmental Conditions
    - Electrical/EMF Conditions
    - Mechanical Conditions
    - Climatic Conditions

Including but not necessarily limited to

STANAG 3102 FS Ed. 6	Flight Safety Cooperation in Common Ground/Air Space
STANAG 4370 Ed. 4	Environmental Testing
STD AFAP-01 Ed.3	NATO Reaction to Fire Test for Materials – Policy for the Pre-Selection of Materials for Military Applications.

Table A-2 Rationale for Maximum Head Borne Load and Moment of Inertia (MOI) Targets

Condition*	Additional Mass on Head (kg/kg of head form)	MOI about Vertical axis (kg-cm^2)
Head form (mass = 3.6424 kg)	1	1.00
HGU-56P helmet	1.41	1.20
HGU-56P helmet with NVG down (no batteries)	1.56	1.32
HGU-56P helmet + NVG down + batteries	1.66	2.99
HGU-56P helmet + NVG down + batteries + CW	1.91	4.55
System Design Target (150 grams) (1/2 weight of battery pack)	**1.60**	**2.15**

*Data Provided by Val Cartier Report to Capt. Gabrielle Chafe on Mass, COG and MOI for Griffon Flight Crew head gear. March 2014.

Annex B Determining the Length of the Spring Cable

(Report Prepared by Ms. Jennifer Lahey)

Introduction

The main musculoskeletal concern of CH-146 Griffon aircrew is neck pain. In order for the aircrew to complete its missions in day or night environments, they must use a variety of head and neck movements. When night vision goggles (NVG) are worn on the Griffin Helicopter helmet at night, the main problem for the aircrew is the increased heavy mass located at the front of the helmet. To counterbalance the NVG, batteries and a counterweight are placed at the back of the helmet. This additional mass puts even more demand on the neck muscles in order to stabilize and control head movements. In particular, extra effort is needed by the small muscles of the head-to-neck joint (atlanto-occipital joint) to counterbalance the NVG. As well, all of the weights act a considerable distance from the centre of gravity thus increasing the moment of inertia such that motion in the flexion/extension plane is almost 4x as much as the head alone. The resistance in side-to-side rotation is 6x the moment of inertia when compared to the head alone.

One solution to help reduce the inertial effects of the NVG and counterweights is to develop a new counter-measure (NCM). Although we are unaware if the device will reduce neck pain, we have shown with a biomechanical model that the device will reduce force requirements from the neck musculature. The concept for this ergonomic aid is to use a spring-system, anchored at the back of the helmet and vest, to create an assistive moment so that the neck muscles do not have to work as hard. The NCM device could then be tested to see its effect ibn reducing neck pain.

Purpose

The purpose of this research sub-study was to determine the maximal length of cable needed in the NCM system to permit maximum range of motions at the atlanto-occipital joint (head only) and neck joints (head to C7). The rationale for this study was to provide our design engineers with essential information about head and neck postures that fixed wing aircrew are exposed to when performing essential in-flight tasks. Rather than examine the range of motion (ROM) in degrees, our specific purpose was to measure the distance that the NCM spring cable must travel to permit all possible motions required of fixed wing aircrew while performing their duties.

Methods

The protocol described below was cleared through the University's Research Ethics Board. Twelve medium and tall male participants from the student population at Queen's University in Kingston, Ontario volunteered to participate. This skewed sample of male participants was recruited because we needed to know maximal distances of NCM cable travel, not the average distances for each sex. Upon arrival in the Ergonomics Laboratory at Queen's University, the nature of the research and procedures were explained to each volunteer before they signed a consent form.

Wearing a helmet has been shown to restrict the range of motion in the neck. Because this restriction of motion may vary between participants, we elected to measure ROM, as defined by cable length, in both a helmet and no-helmet conditions. Unfortunately at the time of testing, the HGU 56P helmet was not available. To accrue the necessary measurements in time for the design phase, a football helmet was used for the helmet condition. A comparison of these two helmets is illustrated in Fig. 1. The Griffin Helicopter helmet on the left side is wider than the football helmet and it is much shorter at the neck line. It was felt that only one ROM measure (neck extension) would be affected by this difference in dimensions.

Fig. 1. Illustration of the Griffin Helicopter helmet on the left and the football helmet on the right.

First, each participant was required to sit erect on the same chair and gaze at a red X placed on the far wall that was positioned at eye height for each participant. The erect posture and gaze point represents the starting position for each ROM task. This upright natural position without the football helmet is illustrated in Fig. 2. The blue dot represents the participant's seventh cervical vertebrae (C7) and the piece of tape in the participant's hair represents the external occipital protuberance (inion process) on the skull. These locations represent the approximate locations of the NCM attachment points. An upright natural position with the football helmet is illustrated in Fig. 3. Although the external occipital protuberance is no longer visible, a dot placed at the bottom center of the football helmet and a tape measure was used to find the same location on the skull.

Fig. 2. Upright natural position without helmet.

Fig. 3. Upright natural position with football helmet.

Figures 4 and 5 provide additional measurements in relation to skull anthropometrics to assist in locating the centre of gravity of the head. In Fig 4, the blue dot represents the base of the helmet with width-based dimensions while Fig. 5, illustrates the starting position as the distance from the ear canal to the back of the helmet.

Fig. 4. Blue dot represents external occipital protuberance.

Fig. 5. Upright natural position with football helmet – side view.

The following pictures depict the essential postures performed by the participants to replicate fixed wing aircrew during in-flight tactical operations. These tasks were repeated while wearing: 1) Griffin HGU 56P helicopter helmet, and 2) without the helmet (control condition). Although the participants were measured in the football helmet and not measured in the Griffin helicopter helmet, the postures were assumed to be similar. All measures were taken with a tape measure to determine the distance between C7 and the mark on the helmet/scalp with each measure repeated twice. The testing session lasted ~ 30 minutes per participant.

Fig. 6. Upright natural position.

Fig. 7. Upright natural position – side view.

Fig. 8. Forward flexion – head only motion.

Fig. 9. Forward flexion – head and neck combined.

Fig. 10. Backward extension – head and neck.

Fig. 11. Rotation of head to right – neck neutral.

Fig. 12. Rotation to the right of head and neck combined.

Fig. 13. Rotation of head to left – neck neutral.

Fig. 14. Rotation to the left of head and neck combined.

Fig. 15. Lateral bend to the left.

Fig. 16. Lateral bend to the right.

Results and Discussion

Table 1 depicts three important measures: the size (height and mass) of the participants and the distance from the external occipital protuberance (EOP) to the spinous process of C7. Our participant selection criteria was developed to ensure that this sample of male participants was larger than average so that the spring cable for the NCM would be designed for the maximum excursion needed. Since the average male is 1.76 m and has a mass of 88.68 kg, according to Centers for Disease Control and Prevention, our data show that we did succeed in selecting participants who would probably exceed the anthropometry of most pilots and flight engineers, especially in terms of stature, a key variable in determining cable excursion length. Table 1 also identifies the average, standard deviation and maximum and minimum distance from EOP to C7. Based on these data, a minimal cable length must be greater than the reported maximum value (14 cm).

Table 1. Heights, Body Weights and Measured Natural Upright distance (No Helmet)

Variables	Mean	S.D	Max	Min
Height (m)	1.81	0.07	1.97	1.72
Weight (kg)	81.12	9.46	108.86	72.57
EOP to C7 (cm)	11.11	1.46	14	8.9

Tables 2 and Table 3 report the additional length needed in the cable for no helmet and helmet respectively when the head is moved in various directions from the starting location of upright sitting posture. All data are reported as differences from the standard starting location. The advantage of reporting these values in Table 2 is to confirm that data from Table 3 is reasonable for the helmet-based condition in Table 3. Negative values represent when the spring cable would be slack (i.e. head extension). The largest reported value for any of the movements is 5.2 cm for the helmet condition during forward flexion that involved both the head and neck. Adding this information (5.2 cm) to the baseline length (14 cm) from Table 1, the cable must be at least 19.2 cm long. In addition, a margin of safety should be built into the design.

Table 2. No Helmet Condition: Distances (cm) from External Occipital Protuberance to C7 process

Motions Performed by Participants	No Helmet	No Helmet	No Helmet	No Helmet
Measures (cm)	**Mean**	**SD**	**Max**	**Min**
Forward flexion – head and neck	2.6	0.7	3.7	1
Forward flexion – head only motion	1.9	0.6	2.7	0.5
Rotation head to R/L -neck neutral	0.1	0.9	2.05	-1.8
Rotation of head & neck R/L - max	0.1	0.9	2.15	-1.8
Backward extension – head and neck	-6.6	1.6	-4.4	-10.1
Upright natural (starting position)	0.0	0.0	0	0
Lateral bend R/L	-0.8	0.8	0.15	-2.8

Table 3. No Helmet Condition: Distances (cm) from External Occipital Protuberance to C7 process

Motions Performed by Participants	Helmet	Helmet	Helmet	Helmet
Measures (cm)	**Mean**	**SD**	**Max**	**Min**
Forward flexion – head and neck	3.4	1.1	5.2	1.1
Forward flexion – head only motion	2.5	1.0	3.9	0.6
Rotation of head to R/L -neck neutral	1.6	1.0	3.1	-1.3
Rotation of head & neck to R/L	1.9	1.5	4	-2.4
Backward extension – head and neck	-8.8	2.3	-6	-15.4
Upright natural (starting position)	0.0	0.0	0	0
Lateral bend R/L	-0.7	1.0	0.5	-2.9

Limitations

There are a number of limitations to this study that may have caused some errors. One of the errors was due to the fact that the Griffin HGU 56P helicopter helmet was not available for the study; therefore, a football helmet had to be used to generate the measurements and range of motions. As shown in Fig. 1 the HGU 56P helmet is much shorter at the back and wider at the ears than the football helmet. This could lead to inaccurate measurements. This difference in distance between the bottom of the football helmet to the External Occipital Protuberance (EOP) is 6 cm. Since the helmet attachment point for the NCM is over the EOP, this measure must also be added to the cable length. Another error was the fact that a tape measure was used for recording the data. Although each measure was recorded twice, this strategy could result in a misreading or rounding error leading to inaccurate results. Finally, the participant may not have started in the neutral sitting posture or challenged themselves to their maximal ROM, which would also have affected measurement accuracy.

Conclusions

This research sub-study was conducted to gather information about head and neck ranges of motion that could occur in pilots or flight engineers at the atlanto-occipital joint (head only) and head and neck joints (atlanto-occipital joint to C7) when performing essential in-flight tasks. This measurement was needed to determine the length of cable required in the design of the NCM device. By using range of motion test protocols, we were able to measure the length of the cable needed between the two anchor points of the NCM on the helmet and the upper back. Based on these data, the minimum length of the cable should be 25 cm. This cable length is made up by measures of: (i) the height of the EOP to C7 (14 cm) plus (ii) the longest measured length during ROM tasks (i.e., flexion of the head and neck) (5.2 cm) plus (iii) an additional length for safety reasons (5 cm).

This page intentionally left blank.

Annex C Preliminary Evaluation of Preferred Spring Tension

(Report Prepared by Ms. Jennifer Lahey)

Introduction

Neck pain is the main musculoskeletal concern of CH-146 Griffon helicopter aircrews. This is due to the variety of head and neck movements during missions in day or night environments. When night vision goggles (NVG) are worn, there is an increased mass on the front of the helmet. The current approach is to add a counterbalancing force on the back of the helmet equal to the NVG weight. However, this solution is not effective when one bends one head forward as the head's mass, NVG, batteries and counterweights all act downward thus increasing the demand on the neck muscles. As well, all of the weights act at a considerable distance from the head's centre of gravity thus increasing the moment of inertia such that motions in the flexion/extension plane are almost 4x as much as the head alone and the resistance during side-to-side head rotation is 6x the moment of inertia when compared to the head alone. An example of the moments required to counterbalance these loads is shown in Figure 1.

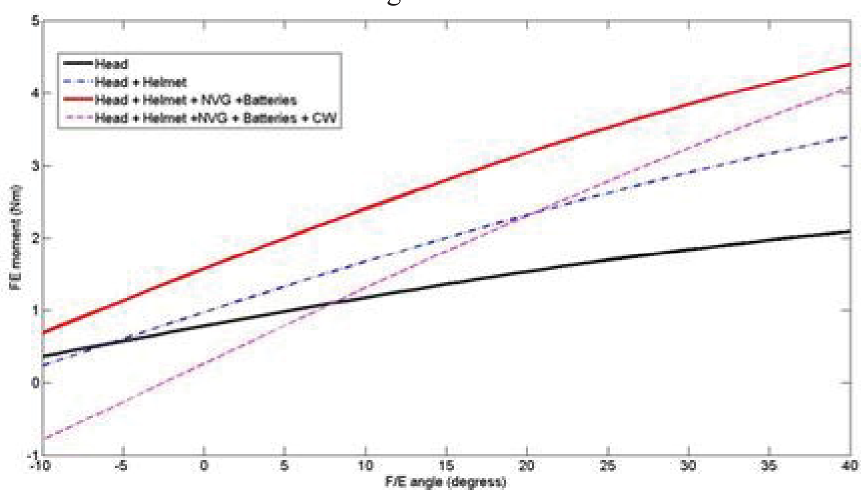

Figure 1. Flexion-Extension (FE) moment at the neck as a function of the neck FE angle. Each line indicates the estimated moment based on different head/helmet systems configurations as described in the legend (extracted from main report).

To aid the neck muscles in counterbalancing the NVG, our research team was tasked with developing an ergonomic assist for the neck muscles; referred to as the new counter-measure (NCM). The prototype design of the NCM device consisted of a constant tension 8 N variable length spring that was anchored at the back of the helmet and to the vest just below C7 via durable double-sided Velcro™ (Figure A2). This cable was protected in a shielding conduit and threaded through the vest collar in order to position it at the nape of the neck. The cable could be released from the helmet attachment point using a finger strap to lift the adjustment mechanism from its holder. This would allow the adjustment mechanism and attached cable to recoil into the lower attachment device but leave it easily accessible above the collar. The adjustment mechanism changed the moment arm of the cable, resulting in different force levels called light (8

N), medium (8.4 N) and heavy (8.8 N). The objective of the design was to have the flight crew change the cable's applied force depending on the tasks they were performing.

Figure 2. The NCM device replaces both the battery pack and counterweight. It is attached on the helmet and vest with an adjustable spring cable providing a counterforce of 8N + 0.8 N.

Forde et al. (2011) used a 3DMatch posture-matching program (Callaghan, 2006) at 5 Hz (Andrews and Callaghan, 2003) to, among other things, determine the posture of pilots when wearing NVG during night flights (Table 1). These results were verified by our research team during a night flight in Phase 1 of this project (Fischer et al., 2013). These data were used to help create the methodology used in this study. In addition, the research team needed feedback on the design concept and whether the new design was preferable to the current counterbalancing system. As well, it was important to know if the adjustment settings were adequate to accommodate different tasks and personal preferences.

Table 1. Partial data from Forde et al. (2011) related to neck postures when wearing NVG.

Neck Motion (night flights only)	Mild (0 º - 10º)	Moderate (10 º – 30 º)	Severe (> 30 º)
Flexion/Extension (% time)	13.5 %	74.5 %	10.8 %
Rotation (% time)	35.1 %	63.1 %	1.3 %
Lateral Bending (% time)	86.4 %	13.4 %	0.2 %

Purpose

The purpose of this pilot study was to determine which of four (4) different conditions (current, and light, medium, or heavy cable applied forces) resulted in the least effort when performing 6 typical aircrew tasks. This evaluation was limited to subjective opinions only. We hypothesized that subjective perceptions of effort would adequately inform the research team of the efficacy of a NCM system with adjustability. In addition, this pilot study would inform the research team of any changes needed to improve the NCM design.

Methods

This research project was cleared by the University's Research Ethics Board. Because we were limited to one large HGU-56P helmet worn by CH-146 Griffon helicopter aircrew, we selected a skewed sample of large and medium male participants from the student population at Queen's University in Kingston, Ontario. There were eight (8) participants who were 1.81m ± 0.07m in height and 81.12kg ± 9.46 in weight (kg). Upon arrival in the Ergonomics Laboratory at Queen's University, the nature of the research and procedures were explained to each volunteer before they signed an ethics consent form.

The protocol consisted of completing the ethics procedure, followed by a detailed explanation and demonstration of each of the six tasks. Participants were asked to perform the tasks before donning the helmet and encouraged to ask questions. Then, the data sheet was explained so that the participants knew the baseline (current) condition was first and given a score of 4 out of 7 by the researchers. The score of 4 allowed the NCM conditions to be either given a score above or below the baseline condition. Then, participants donned a standardized HGU-56P helmet with replica NVG so that it could be adjusted and tightened to make it comfortable and stable on participants' heads. The scoring sheet and location of the scoring sheet are shown in Figure 3.

Comparison of Different Settings for HeadsUp Device

Code # __________ Date/Time ____________

Tasks	Baseline	Setting __	Setting __	Setting __
	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7	1 2 3 4 5 6 7
1. Rotation	○○○●○○○	○○○○○○○	○○○○○○○	○○○○○○○
2. Flexion	○○○●○○○	○○○○○○○	○○○○○○○	○○○○○○○
3. Right Complex	○○○●○○○	○○○○○○○	○○○○○○○	○○○○○○○
4. Left Complex	○○○●○○○	○○○○○○○	○○○○○○○	○○○○○○○
5. Horiz. Plinth	○○○●○○○	○○○○○○○	○○○○○○○	○○○○○○○
6. Static Hold	○○○●○○○	○○○○○○○	○○○○○○○	○○○○○○○

Overall, rank the 4 settings (highest to lowest) Why?________________________

____

Other comments ________________________________

Figure 3. Data sheet and its location for recording perception of each task and condition with a score of 4 used to represent the current (baseline) condition.

The protocol required 4 conditions to be performed. The baseline (current) condition was performed first, followed by light, medium and heavy presented in randomized order. The baseline condition consisted of the helmet, NVG, counterweight and battery pack and weighted 12.2 N. The 'light' setting of the NCM device applied 8.0 N counterforce when the adjustable lever was elevated one notch. The 'medium' condition applied a 8.4 N counterforce when the lever was elevated 2 notches, and the 'heavy' condition applied a 8.8 N counterforce when the lever was adjusted 3 notches. These conditions shown in Figures 4.

A. Current Condition **B.** Light Condition **C.** Medium Condition **D.** Heavy Condition

Figure 4. The four testing conditions (A-D). Note the cable and position of the adjustable lever on the back of the helmet in B, C and D.

Each participant sat erect on a chair and gazed at a red X placed on the far wall that was positioned at eye height for each participant. This posture and gaze point represented the starting position for all tasks. The tasks were block randomized within each condition with participants blinded to the NCM conditions. The tasks were called: 1) head rotation (~40º) head in level flight; 2) head flexion (~40º) in level flight; 3) landing and take-off preparations (complex motions of down, up, behind to the right; 4) to the left; 5) head motions (right, down, left) in the posture of FE during landings; and (6) chart recording in a static forward leaning posture. Each of these tasks will be described below.

1. Neck Rotation

Task #1 is illustrated in Figure 5. It involved 10 repetitions of head rotation to ±40° paced by a metronome in 4 seconds/rotation.

Figure 5

2. Neck Flexion/Extension

Task #2 is shown in Figure 6. It involved 10 repetitions of head flexion to ±30° and extension to -10º to a metronome in 4 seconds/repetition.

Figure 6

3. Complex Head Motions (To Right)

Task #3 is illustrated in Figure 7. Three repetitions were completed in the pilot position where the participant looked: (a) down at the controls, (b) down and to the side to see out lower window, (c) sideways to look out the side window, (d) up at upper side controls and (e) backward to see behind. To assist the participants, each location was marked by a X either on the floor and wall or by an object that needed to be spotted. The specific targets were identified verbally by the investigator as well, so that participants could focus on their perception of neck effort rather than

remembering the target locations. The pace was controlled by the investigator so that each posture was held for around two seconds.

4. Complex Head Motions (To Left)

Task #4 was a repeat of Figure 7 but to the left side.

Figure 7. The complex motions to the right (except up to side) show the participant in the pilot's posture.

5. Flight Engineer Landing Posture.

Task #5 is shown in Figure 8. This task was designed to mimic Flight Engineers postures during landing and low flying maneuvres. Each participant lay on the plinth with their head and shoulders over the edge. Then, they completed 5 repetitions of +90°, down, - 90° head rotations to simulate looking at the rotor, under the helicopter and forward for landing.

Figure 8. A simulation of Flight Engineers' postures during landing and low flying maneuvres.

6. Static Hold Posture

Task #6, illustrated in Figure 9, was the static hold posture with the participant sitting in the chair leaning forward for 1 minute. This sustained posture simulated a co-pilot's posture when developing routes or entering map coordinates. Participants were encouraged to perform some task like answering their email to keep busy.

Figure 9.

Results and Discussion

The results will be presented by each task followed by a comparison across all tasks. In all Figures below, the y axes represents a 1-7 point subjective rating with 4 fixed as the score for the baseline condition. Numbers that are less than 4 indicate that a system is poorer than the baseline condition and scores greater than 4 indicate that a system is better than the baseline condition.

1. Comparison of Simple Tasks

Figure 10 represents the most common postures assume by pilots during level flight as 88% of the time their heads are stationary or moving within 30º of neutral (Forde et al., 2011).

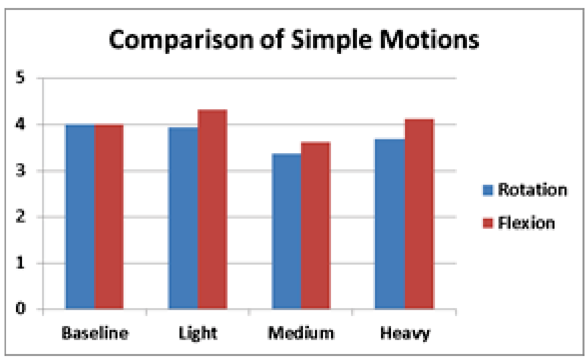

Figure 10. A comparison of Rotation and flexion/extension across conditions.

During head rotation (blue bars), the baseline condition was thought to be better that all three NCM conditions. As shown in Figure 11a, the batteries and counterweights have an equal and opposite weight of the NVG. The NCM design was not advantageous since the cable was attached at an angle to the desired rotation as both attachment points were fixed. This required participants to use some additional neck muscle force to rotate the head against the cable resistance. If a NCM design allowed the upper cable attachment point to rotate left and right on a bar, this would alleviate that problem.

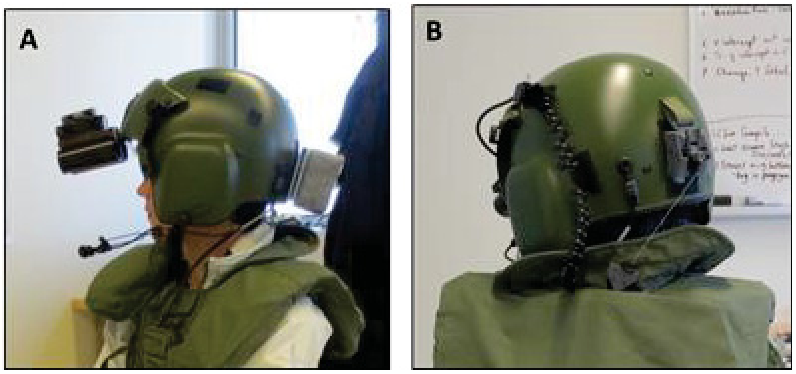

Figure 11. A) a demonstration of the balanced forces created by the current system. B) shows that the cable, which applies a constant force, would resist rotation during turning but assist rotation on return to a neutral posture.

In neck flexion/extension (red bars in Figure 10), the NCM device scored better that the baseline condition for the light and heavy conditions. It was surprising that this result was not the same for the middle condition. One reason the baseline condition was not favoured was because of the added weight that the neck muscles must counteract as the participants leaned forward. In Figure 12a, the flexed neck posture is not dramatic. However, for the flight engineer during landing maneuvres, the total weight of the batteries and counterweight must be borne by the neck muscles. This evidence supports the results in Figure 10 and may be the reason that some flight crew members do not like to wear the counterweight.

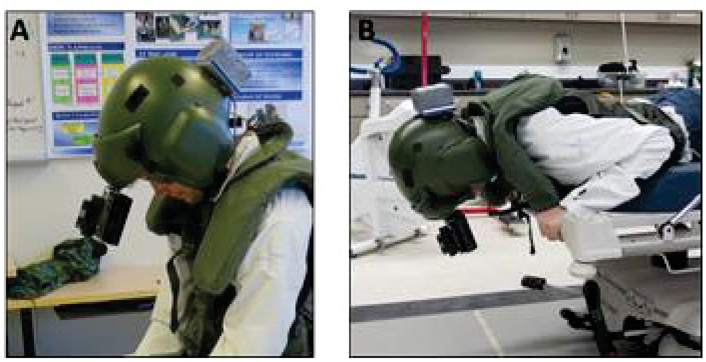

Figure 12. A) When the head is bent forward, some of the counterbalance's weight is borne by the neck muscles. B) When prone, all of the weight of the counterbalance and batteries is borne by the neck muscles.

2. Comparisons of Complex Tasks

Figure 13 depicts head motions more indicative of takeoffs or landings, spotting other aircraft during flight or looking for targets on the ground. The right complex head movements (blue) was not as highly ranked as the baseline condition. Perhaps this was due to interference with the communication system. However, when looking to the left (red) it is undoubtedly preferred over the baseline condition. As before, the middle condition was confusing in that it did not follow the

pattern of the light and heavy conditions; however 4/5 conditions showed that participants preferred the NCM device for complex neck motions.

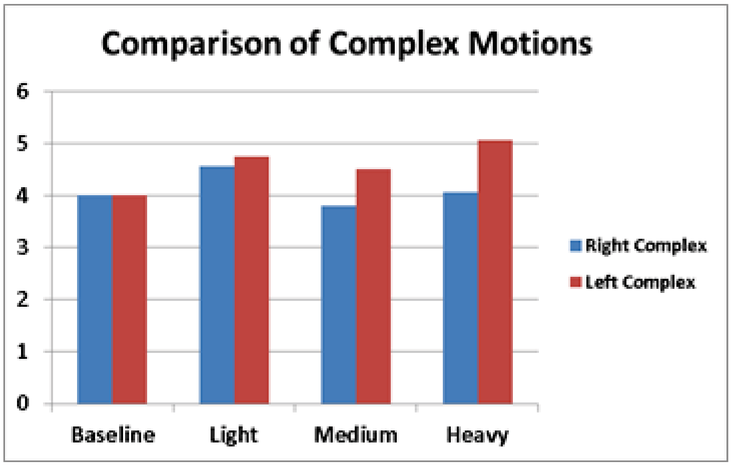

Figure 13. When completing complex head movements to the right (blue), the NCM device is not preferred; however, when turn the head to the left (red), the NCM device is preferred.

3. Comparison of Static and Lying Postures

Figure 14 illustrates the horizontal plinth posture and static hold postures that were also depicted earlier in Figure 12. Undoubtedly the light, medium and heavy conditions were considerably better than the baseline condition. As explained earlier, both of these postures resulted in the neck muscles needing to bear more of the weight of the counterweight and batteries. The NCM device applies a constant force of 8.0 N, 8.4 N and 8.8 N during the light medium and heavy conditions, respectively with no added weight borne by the neck muscles. There is an obvious advantage of the NCM device during these tasks.

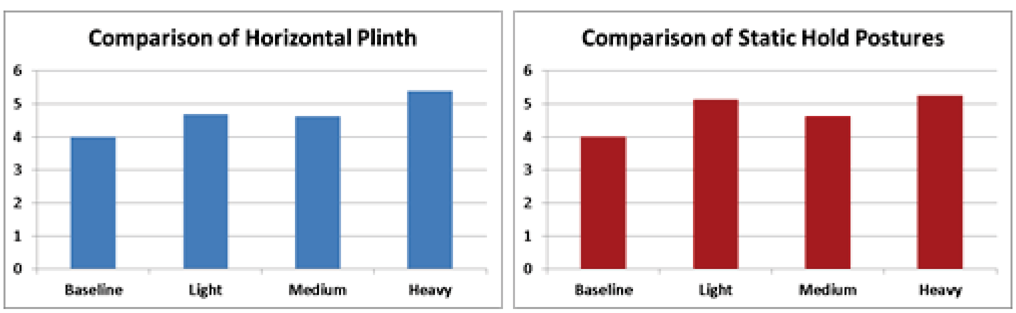

Figure 14. Both the plinth posture (blue) and the static hold postures showed the advantage of the NCM device across all three conditions.

4. Comparisons across all Tasks.

Figure 15 shows a comparison of all of the 6 tasks for each of the 4 conditions. Only during neck rotation was the current condition preferred over some variant of the NCM device. This is probably due to the balance of moments between the NVG and batteries and counterweight as well as a design weakness of the NCM device that applied a counterforce to head rotation. Other information can be gleaned from Figure 15 when examining the NCM device only. First, the light condition (8.0 N) was best for head erect conditions (rotation, flexion and right complex motions). But when leaning forward more dramatically (static and plinth postures), the heavy condition of 8.8N was better than the light and medium conditions. This information would suggest that some variability in the applied force is necessary to accommodate all of the postures and individual preferences of flight crew members.

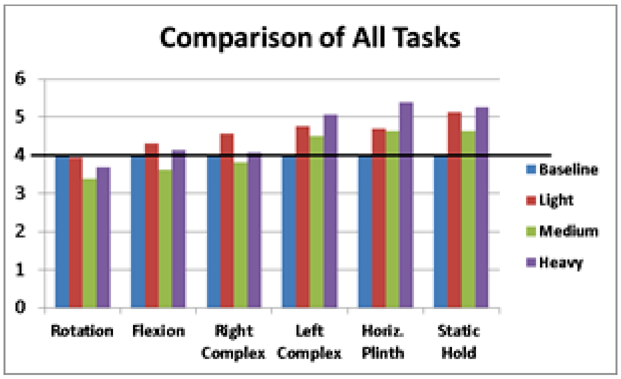

Figure 15. Comparison of all testing conditions for all tasks. The line depicts baseline condition.

5. Ranking Conditions based on Participant Perceptions

Each participant was asked to rank the preferred order for each task. There was a tie for highest ranking: The light condition as preferred for head erect tasks while the heavy condition was preferred for forward bent tasks. The baseline condition was only ranked first for head rotation tasks, while the medium NCM condition never receives a first place ranking. The medium score is somewhat confusing when compared to the light and heavy conditions. More research is needed to explain this oddity.

Table1. A comparison of rank scores across all conditions. The ranking scores occurred after the six tasks were completed within a condition.

Tasks	**Baseline**	**Light**	**Medium**	**Heavy**
Rotation	1	2	4	3
Flexion	3	1	4	2
Right Complex	3	1	4	2
Left Complex	4	2	3	1
Horizontal Plinth	4	2	3	1
Static Hold	4	2	3	1
Average Ranking	**3.2**	**1.7**	**3.5**	**1.7**

Limitations

Some errors may have occurred in the study due to the number of limitations. One concern was the number of participants studied (n=8). Despite this limitation, some design concerns were identified that can be accommodate in the next iteration. Another limitation was that all tasks and conditions were conducted at one time which may have cause muscular fatigue. Despite efforts to reduce fatigue, this may have occurred during the testing. Another possible error was whether participants executed the tasks in the same manner across all conditions. Care was taken to eliminate this possibility; however, no objective measures were taken to ensure this consistency. Finally, it is impossible to assess whether participants were concentrating on their neck muscles and their perception of effort. This may cause some variability in the results.

Conclusions

This pilot study was developed to determine if the NCM system had merit when compared to the standard condition, whether some adjustability was necessary to accommodate all flight crew tasks and identify necessary design changes. Results revealed that the NCM system was preferred over the current system in all cases except head rotation in a vertical position. This was a result of a design weakness in the NCM system that did not reduce the cable tension during rotation. A design change can be implemented to accommodate this concern. A NCM cable light tension force of 8.0 N was better for tasks were participants were in erect sitting whereas a heavy cable tension force of 8.8 N was better when head postures were in forward bending or laying in a prone posture. It is not known if even greater cable forces than 8.8N would be better for the prone situation; this warrants further investigation. These results show that, with further design improvements, the NCM device is superior to the current condition based on participants' perceptions of muscular effort.

References

Andrews, D., Callaghan, J., 2003. Determining the minimum sampling rate needed to accurately quantify cumulative spine loading from digitized video. Applied Ergonomics 34 (6), 589-596.

Callaghan, J.P. (2006) Cumulative spine loading. InW.S. Marras,W. Karwowski (eds). The Occupational Ergonomics Handbook second ed.: Fundamentals and Assessment Tools for Occupational Ergonomics, CRC Press, Chapter 13.

Fischer S, Stevenson JM, Albert WJ, Harrison MF, Bryant JT, Beach TAC, Reid SA, Coffey B. (2013). Near-Term Ideas to Address Aircrew Helmet Systems-Induced Neck Pain: Mitigating Neck Pain in Aircrew. PWGSC Phase 1 Report W7714-125624/001/SV. Queen`s University, Canada.

Forde, K., Albert, W., Harrison, M., Neary, P., Croll, J., Callaghan, J. (2011). Neck Loads and Posture Exposure of Helicopter Pilots during Simulated Day and Night Flights. International Journal of Industrial Ergonomics 41, 128-135.

This page intentionally left blank.

List of symbols/abbreviations/acronyms/initialisms

[Enter list here, if applicable. If not, delete the page.]

DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
R&D	Research & Development

NVG	Night Vision Goggles
CW	Counter Weight
HeadsUp	Code used for new counter-measure device
Device	Code used for new counter-measure device
OC	Occipital Condyles
C1-Head	Atlanto-occipital joint
C1-C2	Atlanto-axial joint
CoG	Centre of gravity
CoM	Centre of mass
3D	Three dimensional (x, y, z)
FE	Flexion/extension force or moment
LB	Lateral bending force or moment
RMS	Root mean square
EMG	Electromyography
RPE	Rating of Perceived Exertion
CPS	Cervical Paraspinal muscles

F	F stands for F-test using when comparing statistical models fitted to the data using least squares. The name was in honour of Sir Ronald A. Fisher who developed this approach.
p	P-value is the probability of obtaining a test statistic result
$n\text{p}^2$	A measure of effect size – also called partial eta-squared
ANOVA	ANalysis Of VAriance – a statistical test